Zentrum für
Klima, Energie und Gesellschaft

Report

Estimated Greenhouse Gas Emissions and Primary Energy Consumption in the Life Cycle Assessment of Transportation Systems with Passenger Vehicles

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Content

Abstract

"There is international consensus that the environmental effects of transportation systems can only be analyzed and compared on the basis of Life Cycle Assessment (LCA) including the production, operation and the end of life treatment of the various facilities".

Life cycle assessment is a method to estimate the material and energy flows of a product (e.g. transportation service) to analyze environmental effects over the entire life time of the product „from cradle to grave".

This project investigates the environmental effects of the various stages in the life cycle of the transportation systems with passenger vehicles. The stages include extraction of raw materials, manufacturing, distribution, product use, recycling and final disposal (from cradle to grave). Life cycle assessment allows the comparison of different systems offering the same transportation service during the same time period and identifies those life cycle phases having the highest environmental effects.

The aims of the project are

- Estimate, assess and document the greenhouse gas emissions and the cumulated primary energy demand of transportation systems with different passenger vehicles
- Develop a tool to assess and compare the environmental effects of various transportation systems with passenger vehicles ("LCA TOOL")
- Apply the methodology of „Life Cycle Assessment" (LCA)
- Provide default data for LCA and give opportunity to make LCA calculation with own data
- Involve stakeholders to maximize acceptance and harmonize inputs

The calculated functional units are

- GHG emissions in g CO_2-eq/km with the %-share of CO_2, CH_4 and N_2O and the different stages in the life cycle, e.g. production, fuel/energy supply, operation and end-of-life.
- cumulated primary energy consumption in kWh_{total}/km with the %-share of fossil and renewable energy

The transportation systems are characterised by the following criteria:

- Type of vehicle: average passenger vehicle
- Propulsion system: ICE – Internal Combustion Engine, BEV – Battery Electric Vehicle, HFC – Hydrogen Fuel Cell, and PHEV – Plug in Hybrid Vehicle
- Fuel/energy carrier: fossil fuels (diesel, petrol, compressed natural gas - CNG); biofuels (biodiesel - FAME, hydrated vegetable oil - HVO, bioethanol - EtOH, compressed renewable gas – CRG; E-fuels - liquid or gaseous fuels produced by using electricity and a carbon source); electricity and hydrogen from different sources
- Type of primary energy: oil; gas; coal; nuclear; biomass from forestry, agriculture and residues; wind; hydro; solar
- State of technology: 2019, 2030, and 2050
- Countries: EU 28 – Europe, AT – Austria, CH – Switzerland, DE – Germany, ES – Spain, IT –Italy, UK – United Kingdom, PL- Poland, PT – Portugal, AUS – Australia, and CA - Canada

In total 64 transportation systems with an average – middle class - passenger vehicle were selected, of which each is analyzed for technology state in 2019, 2030 and 2050. The transportation systems are divided in the following 6 groups

1. Fossil fuel Internal Combustion Engine Vehicle (ICEV) (incl. biofuel blending): 7 systems

2. Fossil fuel and electricity Plug In Hybrid Vehicle (PHEV): 22 systems
3. Battery Electric Vehicle (BEV): 14 systems
4. Hydrogen Fuel Cell Vehicle (HFCV): 4 systems
5. Biofuel Internal Combustion Engine Vehicle (ICEV): 5 systems
6. E-fuel Internal Combustion Engine Vehicle (ICEV): 12 systems

The main findings of the environmental assessment using LCA are:

- An environmental assessment can only be done on the basis of Life Cycle Assessment.
- The contribution of the production and the operation phase to the total cumulated environmental effects is quite different and depends on the system under consideration.
- The GHG emissions and the primary energy demand must be assessed separately, as low GHG emissions from using renewable energy are not connected to a high energy efficiency, as fossil fuel are often more energy efficient but have high GHG emissions.
- The fossil primary energy demand is often correlated with the GHG emissions, except for biofuels due to the N_2O-emissions from agricultural biomass (e.g. HVO from rape seed) and CH_4-emissions from gaseous fuels, e.g. CNG, CRG.
- All three types of GHG emissions - CO_2, CH_4 and N_2O – must be considered. CO_2 most relevant for fossil fuels, CH_4 for natural gas, coal and compressed renewable gas and N_2O for biofuels from agricultural crops.
- Co-products are most relevant for all biofuels, e.g. animal feed for HVO, FAME and bioethanol; heat for FT-diesel and CRG.
- A relevant co-product of electricity for BEV and PHEV is heat from CHP plants that is or can be used as district heat.
- The fossil based transport system, e.g. petrol, diesel, CNG and E-Fuels using current electricity mix, have the highest GHG emissions.
- The transportation systems using (high share of) renewable energy have low GHG emissions, where in some case the GHG emissions from the production phase might become most dominating.
- Even on the long term perspective there is no “Zero-GHG emission” vehicle possible, but low GHG emissions below 25 g CO_2-eq/km are possible assuming further technology development.
- The most relevant parameter for all systems is the energy demand for operating the vehicle. Light and small vehicles and slow driving might also contribute to a low energy consumption of vehicle operation for all considered systems.
- The lifetime of the vehicle and especially of the hydrogen fuel cell and the battery might have a significant influence on the GHG emission from the production phase per kilometer.
- An increasing use of renewable energy for transportation services leads to decreasing GHG emissions. But as the available additional renewable energy should be used efficient also a low primary energy demand becomes more relevant; as e.g. with the same amount of renewable energy more kilometers might be driven with a BEV than an HFCV or and E-Fuel ICEV.

Abbreviations

BEV	Battery electric vehicle
CNG	Compressed natural gas
CO_2	Carbon dioxide
CH_4	Methane
CHP	Combined heat and power (plant)
CRG	Compressed renewable gas
dLUC	Direct land use change
E-fuel	Synthetic fuel, produced with electricity (Power-to-fuel)
EtOH	(Bio)Ethanol
FAME	Fatty acid methyl esther (biodiesel)
FT-diesel	Fischer-Tropsch diesel
GHG	Greenhouse gas emissions
H_2	Hydrogen
HEV	Hybrid electric vehicle
HFCV	Hydrogen fuel cell vehicle
HFC	Hydrogen fuel cell
HVO	Hydrate vegetable oil
Hydro	Hydro power
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
iLUC	Indirect land use change
LCA	Life Cycle Assessment
LUC	Land use change
N_2O	Nitrogen oxide
PED	Primary energy demand
PHEV	Plug in hybrid electric vehicle
PV	Photovoltaics

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1. Introduction

To start with a statement on the methodology for environmental assessments:

"There is international consensus that the environmental effects of transportation systems can only be analyzed and compared on the basis of Life Cycle Assessment (LCA) including the production, operation and the end of life treatment of the various facilities".

2. Aim

The aims of the project are

- Estimate, assess and document the greenhouse gas emissions and the cumulated primary energy demand of transportation systems with different passenger vehicles
- Develop a tool to assess and compare the environmental effects of various transportation systems with passenger vehicles ("LCA TOOL")
- Apply methodology of „Life Cycle Assessment" (LCA)
- Cover different environmental effects e.g. GHG emissions, primary energy consumption,
- Provide default data for LCA and give opportunity to make LCA calculation with own data
- Involve stakeholders to maximize acceptance and harmonies inputs
- Consider broad spectrum of various current and future transportation systems (fossil and biogenic fuels, hydrogen, electricity)
- Present environmental effects in a compact format (e.g. tables, figures in "Fact Sheet") and highlighting most relevant influences
- Present & discuss results and identify main influences

3. Methodology of Life Cycle Assessment (LCA)

3.1 Definition Life Cycle Assessment (LCA)

Life cycle assessment is a method to estimate the material and energy flows of a product (e.g. transportation service) to analyze environmental effects over the entire life time of the product „from cradle to grave".

The environmental effects of the various stages in the life cycle of the transportation systems with passenger vehicles are investigated. The stages include extraction of raw materials, manufacturing, distribution, product use, recycling and final disposal (from cradle to grave)

(Figure 1). Life cycle assessment allows the comparison of different systems offering the same transportation service during the same time period and identifies those life cycle phases having the highest environmental effects.

The most important word in the LCA definition is “estimated“, so all environmental results based on LCA are an estimation, as it is not possible to identify all environmental contributions in the life cycle of a transportation system totally, but due to the strong development of LCA and its databases in the last 15 years the most relevant influences can be identified and calculated on the GHG emissions and the primary energy consumption of different transportation system.

To reflect the LCA definition all results are given in ranges; as by comparing different transportation systems it is only relevant if the ranges are significantly different, partly overlapping ranges between two systems indicate that there is no significant difference between them in terms of GHG emissions and primary energy consumption.

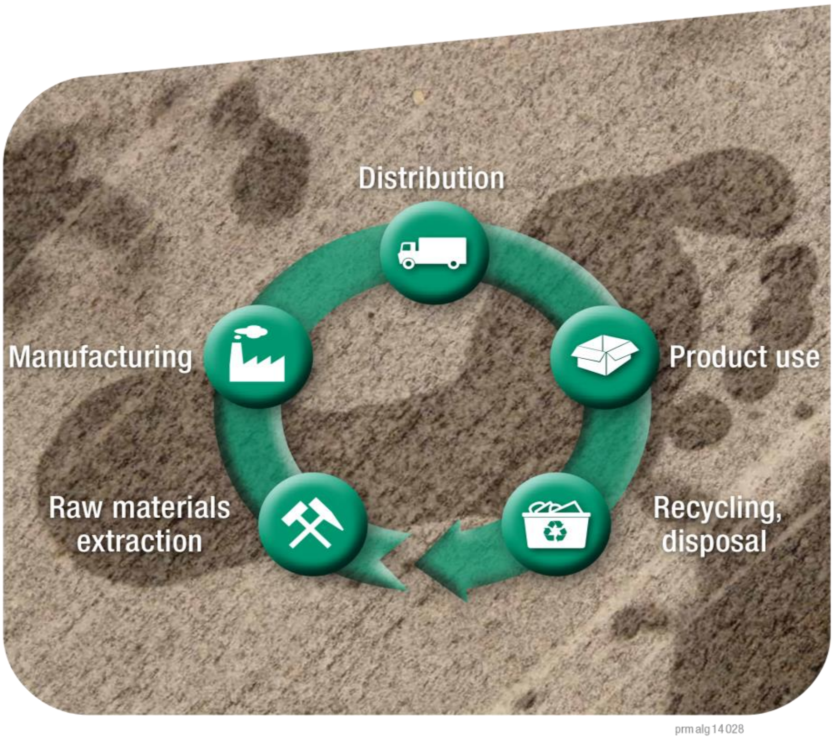


Figure 1: Scheme of life cycle assessment

According to ISO 14,040 a LCA consist of the 4 following phases, which are closely linked during the whole process of applying LCA methodology (Figure 2):

- Goal and scope definition,
- Inventory analyses,
- Impact assessment, and
- Interpretation & documentation.

In the inventory analysis the mass and energy balance is made along the whole process chain to calculate the physical (primary) energy demand and the physical emission of each single greenhouse gas.

In the impact assessment the single energy inputs and emissions are aggregated to the cumulated primary energy demand and the global warming effects by applying the global warming potentials to the single GHG emissions.

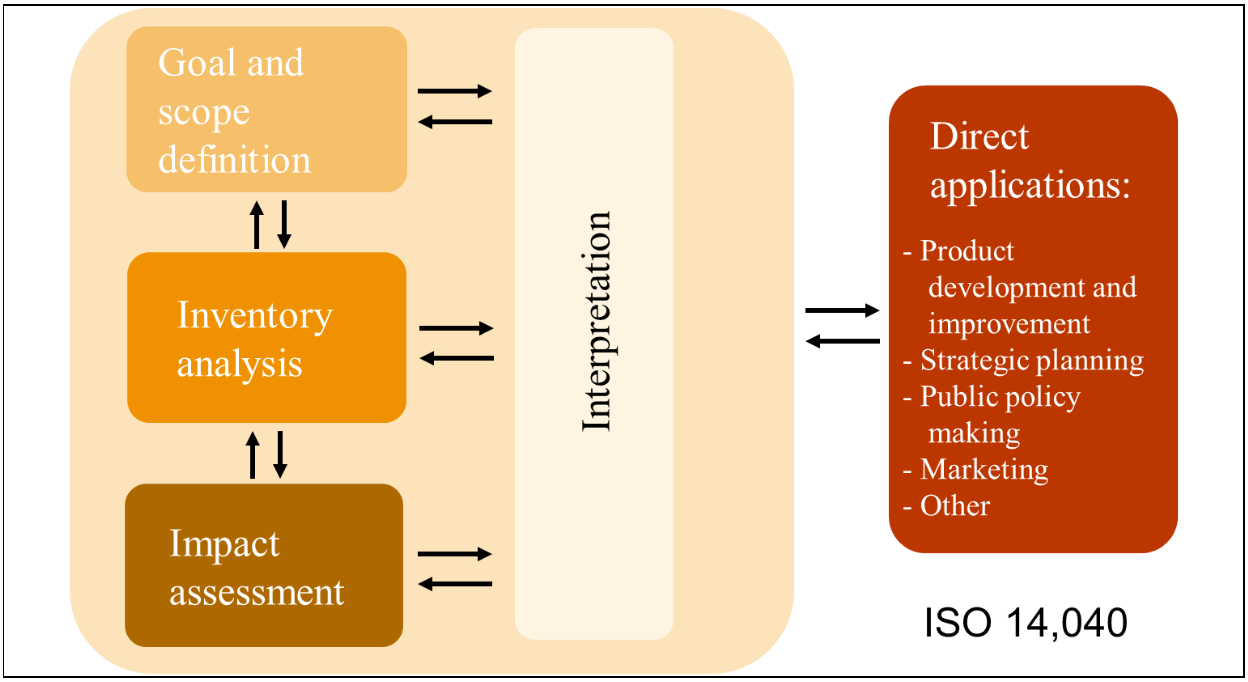


Figure 2: Life Cycle Assessment framework according to ISO 14,040

3.2 System Boundaries

For providing a transportation service all processes must be analyzed from raw material and resource extraction to the vehicle offering the transportation service. The elements and system boundaries of vehicle's LCA include all technical systems using and converting primary energy and material resources to provide the transportation service and contributing to environmental effects.

In Figure 3 the simplified scheme of the process chain for a battery electric vehicle is shown covering the production, the operation and the end of life phase of the system:

- The production phase includes the production of the vehicle and the battery[1].
- The operation phase offers the transportation service by driving the vehicle, charging & fueling infrastructure, electricity grid, electricity production and ends with the extraction of primary energy in nature.
- The end of life phase included the dismantling processes of the vehicle and sorting the materials for reuse, recycling and energy generation.

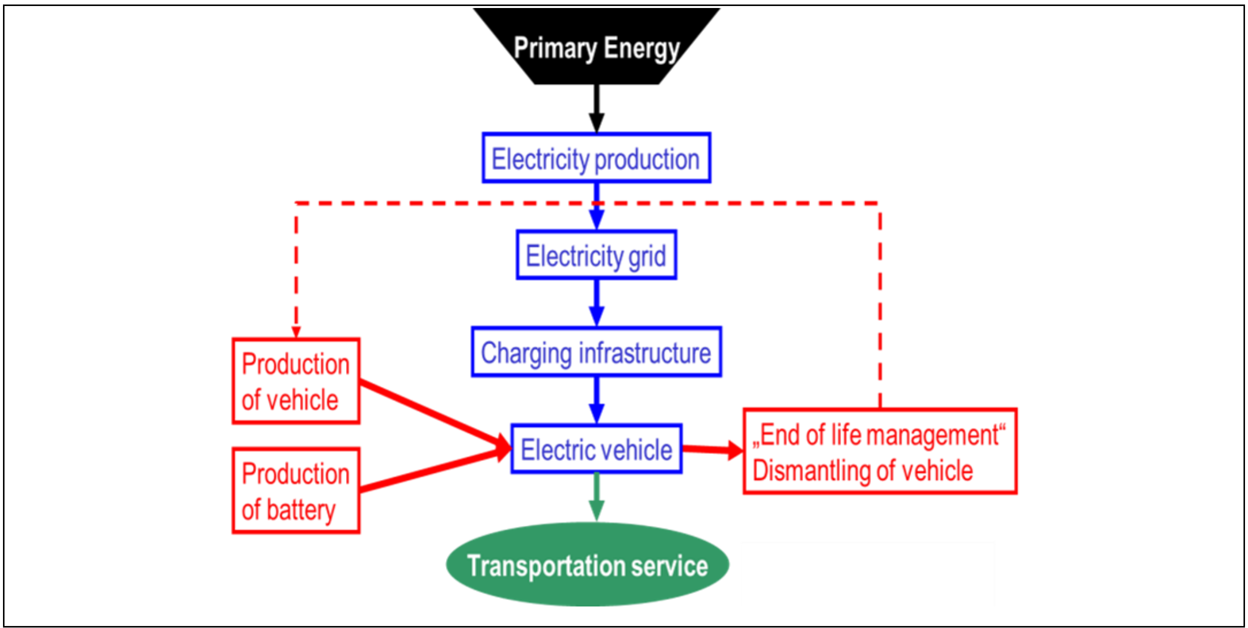


Figure 3: Scope of life cycle assessment - example battery electric vehicle

[1] Additionally, also the spare parts are considered in the production phase, which contribute in total very less.

Life cycle assessment of the three phases in the life cycle of a vehicle – production, operation (including fuel/energy supply) and end of life treatment - cumulates the environmental effects over the whole life time. In Figure 4 this is shown for three hypothetical vehicle types. The cumulated effects over the entire lifetime are then distributed to the transportation service provided in the operation phase (e.g. 150,000 km) to get the specific effects per driven kilometer (e.g. g CO_2-eq/km).

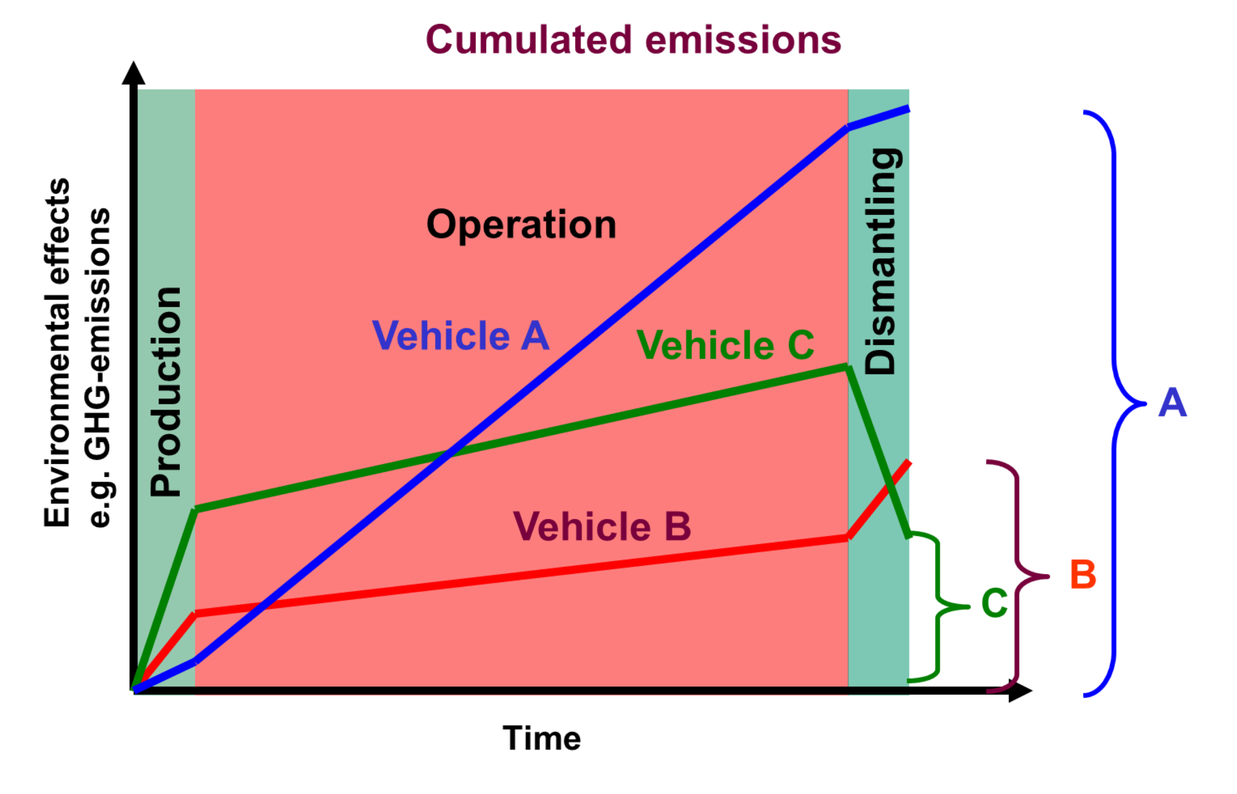


Figure 4: The three phases in the life cycle of a vehicle – production, operation (including fuel/energy supply) and end of life treatment for 3 hypothetical vehicle types A, B and C

All GHG emissions and energy relevant processes to provide a transportation service with a passenger vehicle are considered in the process chain, in which possible co-products, e.g. animal feed from FAME production, district heat from electricity production are also considered with their effects of substituting for other products and services.

As examples in Figure 5 the process chain for a petrol ICE vehicle and in Figure 6 for a battery electric vehicle are shown (for further details on the process chains see chapter 4.4).

In the Inventory Analysis of the LCA (see Figure 2) all physical mass and energy flows e.g. CO_2, N_2O, electricity are analysed or estimated of the process chains. In the Impact Assessment the results of the inventory analysis of the process chains are assessed for the different impact categories, e.g. the single GHG emissions are added up using the global warming potential of the different gases to the global warming potential in CO_2-equivalents (see also chapter 3.4).

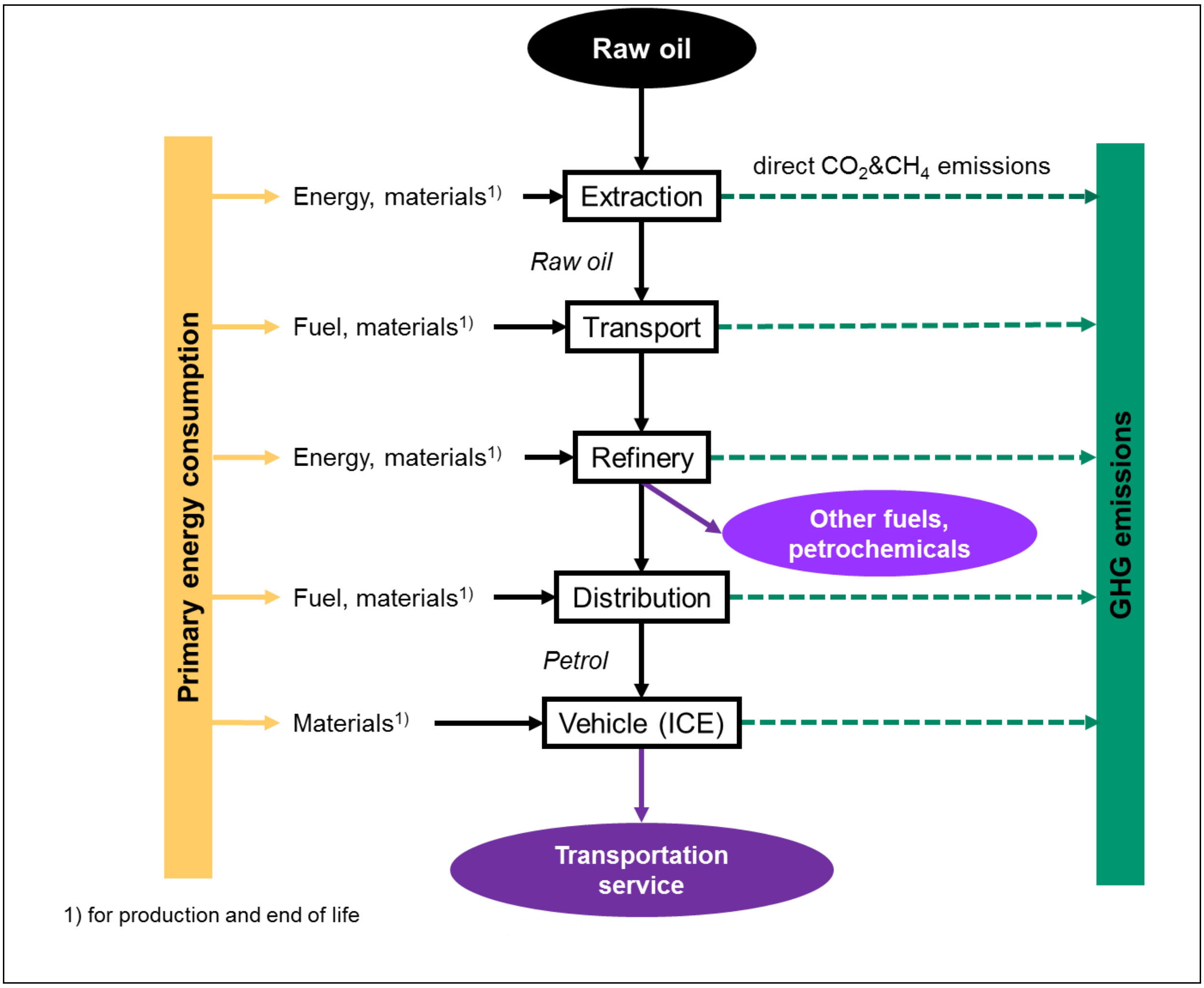


Figure 5: Process chain for petrol ICE vehicle

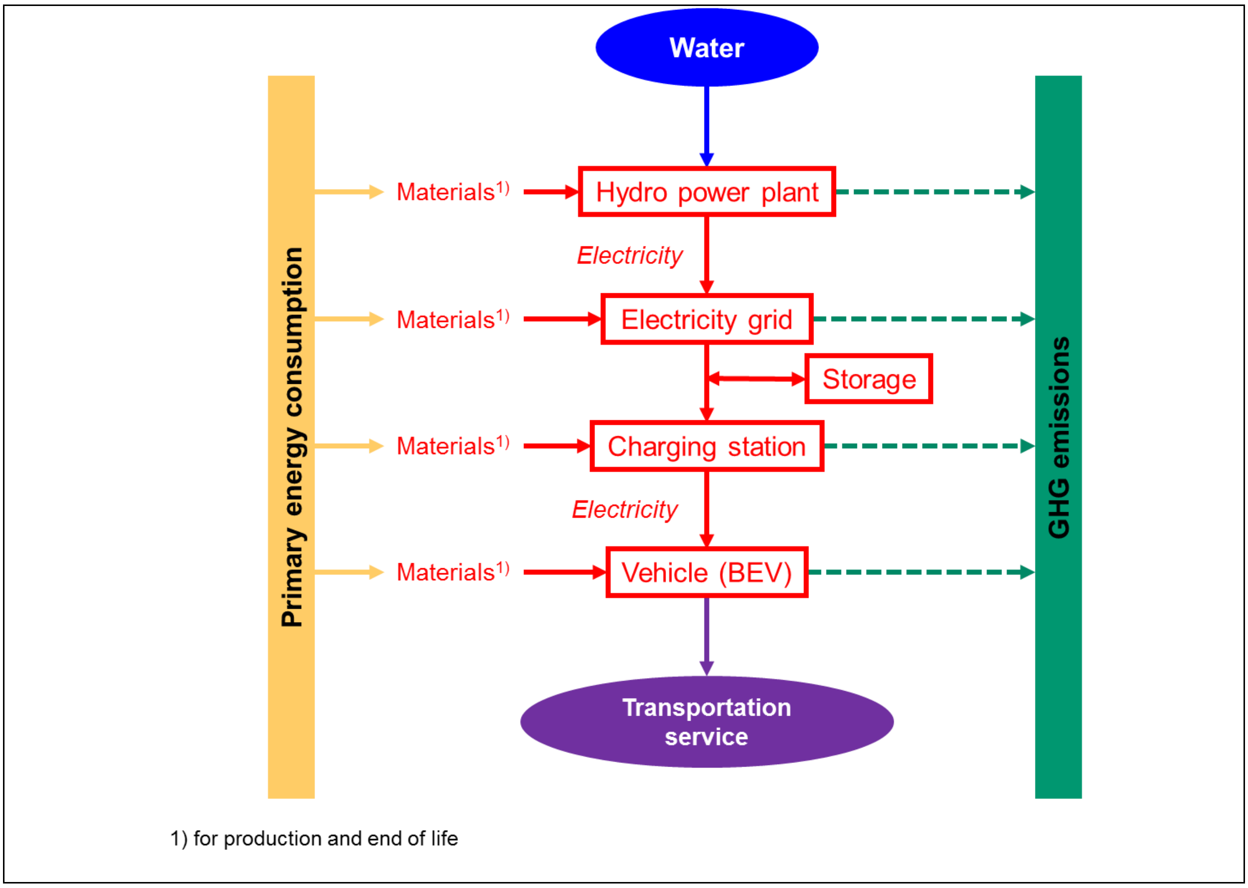


Figure 6: Process chain for battery electric vehicle (example electricity from hydro power)

Depending on the propulsion system and the energy carrier the transportation systems have different GHG emissions and cumulated primary energy consumption, which occur on different locations, at different phases and time in the life cycle. For examples: an ICE vehicle using diesel has the highest CO_2-emissions from the stack of the vehicle operation, a biodiesel ICE vehicle has the highest N_2O-emissions from nitrogen fertilization of the raw material cultivation in agriculture and a current battery electric vehicle using renewable electricity has the highest CO_2-emissions deriving from the battery production in an Asian country.

3.3 Functional Unit

In LCA the cumulated environmental effects over the lifetime are attributed to the functional unit, which is the service of a system that is provided. In this analysis the considered transportation systems provide a transportation service with passenger vehicles. That means that the cumulated environmental effects are attributed to the functional unit of driving

1 kilometer with a passenger vehicle. This functional unit is also used to compare the different transportation systems.

The calculated functional units are

- GHG emissions in g CO_2-eq/km with the %-share of CO_2, CH_4 and N_2O and the different stages in the life cycle, e.g. production, fuel/energy supply, operation and end-of-life.
- Cumulated primary energy consumption in kWh_{total}/km with the %-share of fossil and renewable energy

The functional units are also split up in the following contributions:

- Fuel/energy supply
- Production
- Operation
- End of life and
- the different main process steps and credits given for co-products.

The different possible driving ranges per filling of an ICE, battery electric and fuel cell vehicle are not reflected in this functional unit.

3.4 Environmental Effects

Based on the inventory data two impact categories are assessed:

1. Global warming and
2. Total cumulated primary energy consumption.

Additionally the most relevant aspects of land use change for the raw material production for biofuels on GHG emissions are described. Other environmental effects like emissions to air NO_x, SO_2, PM and their consequential impacts like acidification, ozone formation, and human toxicity are not considered.

3.4.1 Greenhouse Gas Emissions

The greenhouse gas emissions – carbon dioxide (CO_2), methane (CH_4) and nitrogen monoxide (N_2O) – are considered.

As measure of the greenhouse effect of these gases the global warming potential (GWP) is used. This gives the contribution of the different gases to the possible global warming and is expressed in form of an equivalent amount of CO_2. The concept of global warming potential was developed to compare the contribution of the different gases to global warming. The global warming effect of a kilogram gas is expressed with a multiple ("equivalent factor") of the effect of one kilogram carbon dioxide. With the equivalent factors the amount of the gases are calculated in amount of CO_2-equivalents (CO_2-eq.) (IPCC 2019):

- 1 kg CO_2 = 1 kg CO_2-eq
- 1 kg CH_4 = 34 kg CO_2-eq
- 1 kg N_2O = 298 kg CO_2-eq

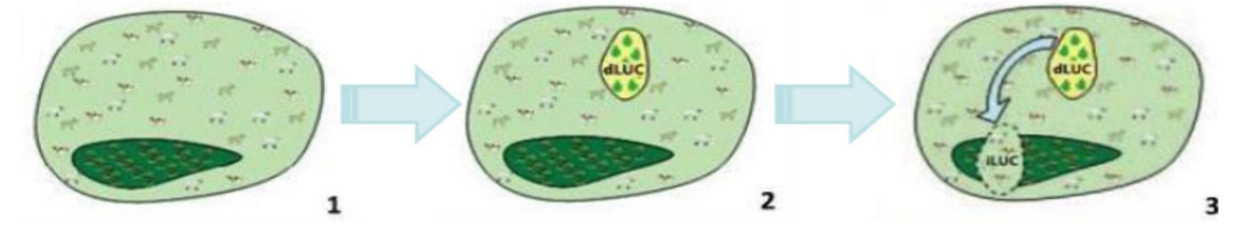
3.4.2 CO_2-emissions from Land Use Change, Biofuels and E-fuels

The biogenic CO_2 emission from the combustion of biofuels is calculated to be zero, as the same amount of CO_2 was up taken during biomass growing via photosynthesis from the atmosphere. This includes the assumption that the biomass is cultivated sustainably.

This accounting system for biogenic CO_2 is used also in the national GHG accounting system following the IPCC guideline for national inventories in the energy sector. Changes and dynamics in the carbon stocks, e.g. the carbon which is stored in plants, litter and soil, in agriculture and forestry are considered in the CO_2 emissions or CO_2 uptake caused by of Land Use Changes (LUC) for biomass used for biofuels.

Analyzing CO_2 effects from land use change two different types of LUC are relevant (Figure 7):

- Direct Land Use Change (dLUC):
- Indirect Land Use Change (iLUC):



<u>Figure 7:</u> Direct Land Use Change (dLUC) and Indirect Land Use Change (iLUC)

Direct Land Use Change (dLUC) occurs if for cultivation of energy crops a land use change takes place, e.g. from pasture to crop land. Direct effects can be calculated, e.g. change of carbon storage pools with the difference of Carbon stocks from pasture and crop land per hectare. This initial effect, which occurs once, must be allocated to the biomass cultivated on the crop land, e.g. for biofuels.

Indirect Land Use Change (iLUC) occurs if existing crop land is now used for energy crops, which was used for other products before. The demand for these products remains and additional land is used causing land use change on global scale, e.g. conversion of natural forests into agricultural land. Indirect effects can be calculated after localization, which is difficult on a global level. The calculation of this initial effect is done one the difference of the carbon stock from forest and agricultural land. But on a physical level a direct allocation of these indirect effects to a specific agricultural crop, e.g. for biofuel or additional animal feed is not possible. The indirect effects are calculated by using economic models and methods. These models give broad ranges of possible iLUC effects of biomass cultivation for biofuels.

For the calculation of GHG emission due to Land Use Change the European Commission uses the GLOBIOM-Modell - Global Biosphere Management Model (Vali H. et al., 2015; http://www.globiom.org/). IIASA's Global Biosphere Management Model (GLOBIOM) is used to analyze the competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors. As such, the model can provide scientists and policymakers with the means to assess, on a global basis, the rational production of food, forest fiber, and bioenergy, all of which contribute to human welfare. In GLOBIOM no distinction between iLUC and dLUC is possible, as iLUC cannot be allocated to certain agricultural activities.

Exemplary in Figure 8 some results of possible LUC effects of biofuel from the GLOBIOM model are shown. The highest possible GHG emissions of LUC are calculated for FAME from palm oil with about 231 g $CO_{2\text{-eq}}$/MJ and from soy oil with about 150 g $CO_{2\text{-eq}}$/MJ, followed by FAME from rape seed oil with about 65 g $CO_{2\text{-eq}}$/MJ. The possible GHG emissions of bioethanol from maize, wheat and sugar beet due to LUC effects are with 14 to 34 g $CO_{2\text{-eq}}$/MJ significantly lower.

In the calculation here the possible dLUC and iLUC effects on the GHG emissions are considered, the main data are shown in Table 28 in chapter 5.4.3.

But in the LCA results in this report and in the tool, only the possible CO_2-effects of dLUC are calculated and included. The possible CO_2-effect from iLUC is shown in background data for information only.

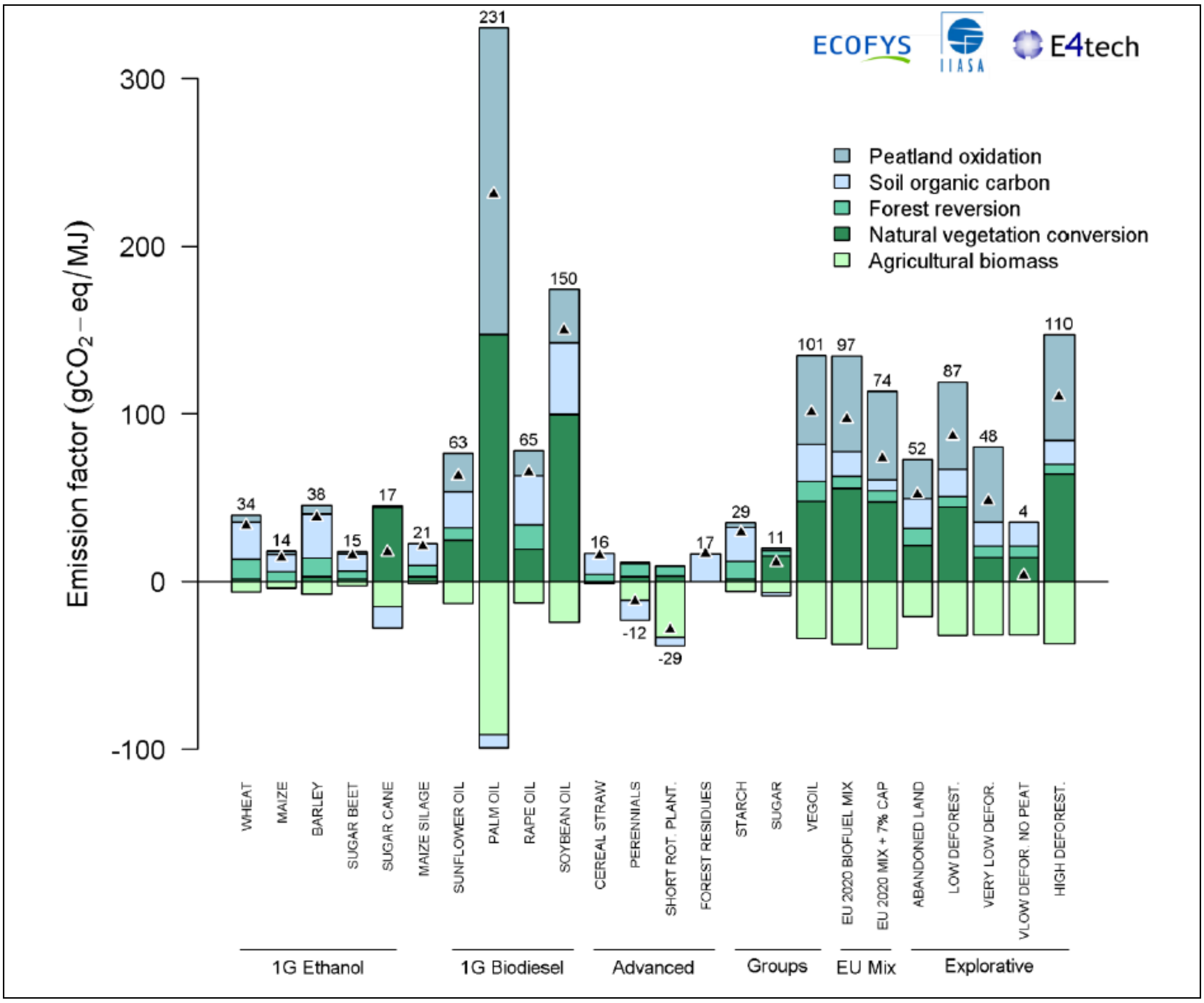


Figure 8: Possible LUC effects on GHG emissions of biofuels (Vali H. et al., 2015)

The CO_2-emissions from the combustion of E-fuels are also calculated to be zero. If the CO_2 derives from biomass combustion it is the same as described for biofuel above. If the CO_2 is taken from the atmosphere via direct air capture, the CO_2 is emitted back to the atmosphere by the combustion of the E-Fuel and the C-cycle is closed again. If the CO_2 for the E-fuel is taken from the flue gas of the combustion of a fossil fuel, it is assumed that the CO_2 is ending up in the atmosphere anyway, which is allocated to the combustion purpose (e.g. heat) of the fossil fuel, so the CO_2 of the E-fuel is calculated in the LCA here to be zero.

3.4.3 Cumulated Primary Energy Demand

Based on the amount and type of final energy carriers e.g. fuels, electricity, the necessary amount of primary energy is calculated to supply the energy needed for the transportation systems. The following primary energy resources are considered:

- Fossil resources: coal, oil and gas,
- Renewable resources: hydro power, biomass, solar, wind
- Other resources e.g. nuclear, waste, residues.

3.5 Comparison to other Methods

Beside the methodology of Life Cycle Assessment there are also other methods to assess the environmental effects. The main other common methods are:

1. WtW-Analysis: Well-to-wheel as sum of Well-to-Tank (WtT) and Tank-to-wheel (TtW) and
2. Method of the Renewable Energy Directive (RED) to assess the GHG reduction of renewable fuels.

Due to the methodological differences the results of these methods cannot be compared to LCA based results.

3.5.1 Well-to-Wheel (WtW)-Analysis

A WtW-Analysis focuses on the analysis of the environmental effects to supply the fuel/energy to the filling station (WtW Well-to-Tank) and to supply the transportation service with the vehicle (TtW - Tank-to-Wheel). But the effects from the production and end of life of the facilities and the vehicles are not considered.

As the production of a battery electric vehicle and a fuel cell vehicle might have significant higher environmental effects than an ICE vehicle, a reasonable comparison with a WtW-Analysis is not possible.

Additionally, as the environmental effects of the production of the facilities are not included in WtW-analysis, this means that the supply of renewable energy e.g. electricity from PV or wind, has no environmental effects, which is not true, as the production of e.g. a PV plant is associated with GHG emissions which must be allocated to the produced electricity during the lifetime of the PV plant. So the WtW-analysis is not an adequate methodology for environmental assessment of transportation services.

3.5.2 Method of the Renewable Energy Directive (RED)

The method of the Renewable Energy Directive (RED, 2009/28/EC), which is the legal basis to assess the minimum necessary GHG reduction of renewable fuels compared to fossil fuels, is beside other simplifications based on the WtW-analysis and is only meant for the analysis of GHG emissions.

The main simplifications are

- Energy allocation for co-products and biofuels
- Production and end of life of facilities is not included
- CH_4- and N_2O-emissiosn from vehicles are set to zero.

3.6 Fact Sheets

Besides the detailed reporting of the basic data and the results, "Fact Sheets" are made for each analyzed transportation system. The Fact Sheet is a compact summary of the main input data and the most relevant LCA results, which make it easy to show main results, communicate LCA results to stakeholders to deepen and create the understanding of the various LCA results of the different transportation systems.

The main aspects in the Fact Sheets are (Figure 9):

- 1 page summarizing main aspects and LCA results
- Generated in LCA TOOL
- For each considered transportation system (incl. state of technology 2019, 2030 and 2050)
- Scheme of process chain: resource to transportation service (incl. co-products)
- Short description of each transportation system
- Main data and assumptions
    - Vehicle
    - Energy carrier (fuel, hydrogen, electricity)
    - Production and dismantling vehicle
- Tables and figures on e.g.
    - GHG emissions (CO_2, CH_4, N_2O)
    - Cumulated primary energy demand (fossil, renewable, other)
- Sources of environmental effects:
    - Vehicle production,
    - Supply energy carrier,

- Vehicle operation

The Fact Sheet was developed and finalized in interaction with the stakeholders reflecting their main interest (see chapter 3.7).

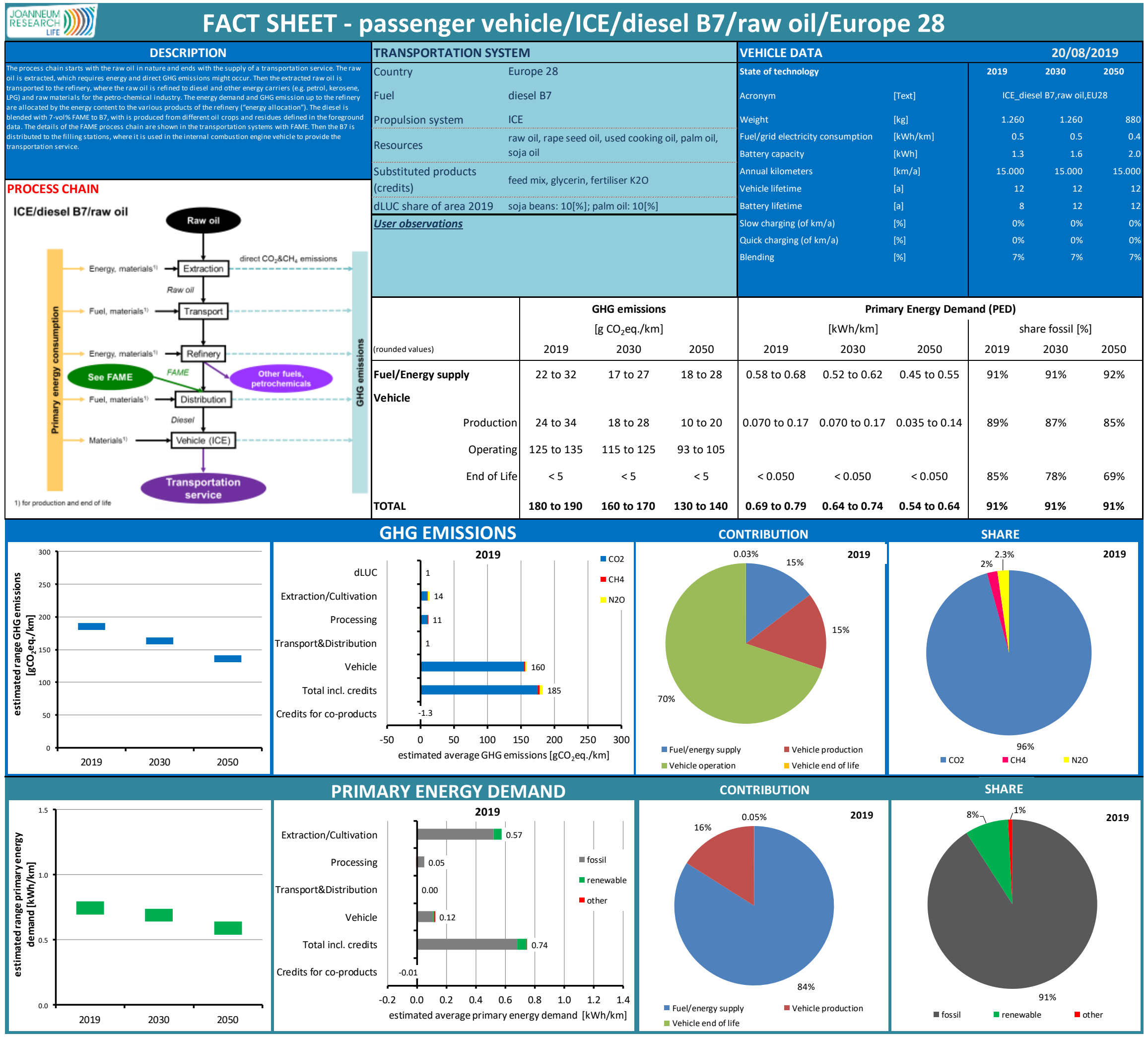


Figure 9: Concept of Fact Sheet

3.7 Stakeholder Involvement

Stakeholders were nominated by FIA and ÖAMTC for the stakeholder process. The stakeholders were involved to exchange information on LCA and to deepen the understanding and acceptance of the LCA methodology, the basic data and the LCA results on the environmental effects.

The stakeholder consultation covers presenting and discussing (Figure 10)

- LCA methodology
- Selection of analyzed transportation system
- Main basic data
- Draft and final LCA results
- Draft and final Fact Sheets
- Introduction to LCA TOOL and
- Training course on LCA TOOL

Based on the feedback obtained in this stakeholder consultation, the draft findings to the above mentioned issues were revised and finalized.

A telephone conference took place each month, where the progress of the analysis were presented and discussed, as well as major decision were taken e.g. selection of the transportation systems, definition of the target group for the tool and the report and the main functionalities of the tool.

The stakeholders invited to these telephone conferences were

- ÖAMTC
- ADAC
- FIA
- TCS

The project, its progress and (initial) results were presented and discussed at the following FIA meetings

- Madrid/Spain: April 26, 2018
- St. Petersburg/Russia; December 4 and 6, 2018
- Brussel/Belgium: May 21, 2019
- Paris/France: June 27, 2019

The participants of the telephone conferences also tested the draft version of the tool and their experiences and feedback were integrated in the final development of the tool. In February also a testing and training course of the tool took place in Vienna at ÖAMTC for the final adjustments of the tool.

- LCA methodology
- Selection of analyzed transportation system
- Main basic data
- Draft and final LCA results
- Draft and final Fact Sheets
- Introduction to LCA TOOL
- Draft and final report
- Training course on LCA TOOL
- Testing of the tool

Figure 10: Overview of the Stakeholder involvement

4. Transportation Systems

4.1 Main Characteristics

The transportation systems are defined by the following 6 characteristics (Figure 11). These 7 characteristics define each single system exactly:

1. Type of vehicle
2. Propulsion system
3. Fuel/energy carrier
4. Type of primary energy
5. State of technology
6. Country (where adequate)

For E-fuels additionally the carbon source, e.g. air, flue gas, is a relevant characteristic of the system.

The naming of each transportation system reflects these characteristics as shown here:

"Vehicle/Propulsion/Fuel/Resource/Technology/Country" e.g. passenger vehicle/ICE/diesel/raw oil/2018.

The main sub-categories of these characteristics are

- Type of vehicle:
    - LDV – Light duty vehicle, representing C-segment vehicle "Golf-Class"
- Propulsion system
    - ICE – Internal combustion engine
    - BEV – Battery electric vehicle
    - HFC – Hydrogen fuel cell
    - PHEV – Plug in Hybrid vehicle
- Fuel/energy carrier
    - Fossil fuels: diesel, petrol, compressed natural gas (CNG)
    - Biofuels: FAME (biodiesel), hydrated vegetable oil, bioethanol, Compressed renewable gas (CRG) (biomethane from biogas upgrading and biomass thermal gasification), FT-diesel, E-fuels (liquid or gaseous fuels produced by using electricity and a carbon source mainly CO_2 from air, fossil fuel or biomass combustion)
    - Electricity from different sources
    - Hydrogen from different sources
- Type of primary energy
    - Oil, gas, coal, nuclear
    - Biomass: forestry, agriculture
    - Wind, hydro, solar
- State of technology
    - 2019
    - 2030
    - 2050
- Countries (only where adequate)
    - EU 28 – European Union
    - AT – Austria
    - CH – Switzerland
    - DE – Germany
    - ES – Spain
    - IT – Italy
    - UK – United Kingdom
    - PL- Poland
    - PT - Portugal

- AU – Australia
- CA - Canada

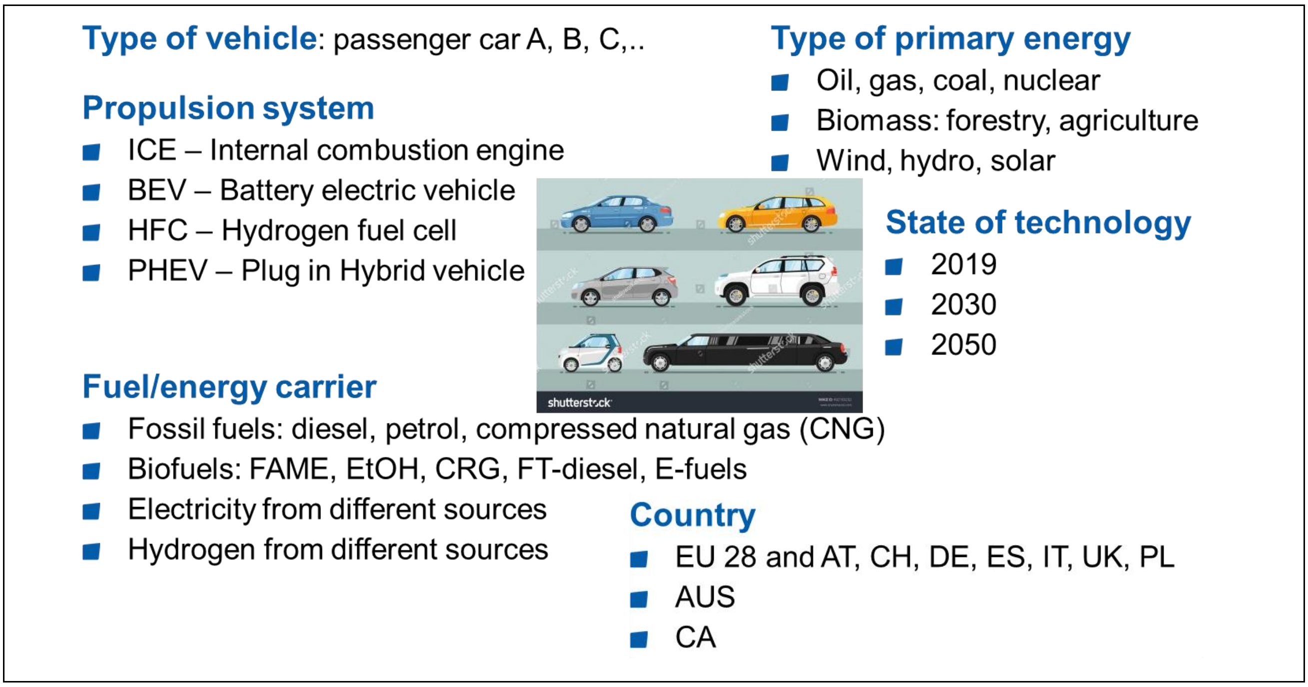


Figure 11: Systematic of Transportation Systems

4.2 Identification of Most Relevant Systems

During the stakeholder process the most interesting transportation systems or combinations were identified covering the following elements to be analyzed:

- Type of vehicle: “Golf-Class” C-segment
- Propulsion system
  - ICE[2] – Internal combustion engine with liquid and gaseous carbon containing fuels from fossil or biogenic origin (no hydrogen)
  - BEV – Battery electric vehicle with different electricity sources and country specific grid mixes
  - HFC – Hydrogen fuel cell (incl. battery)
  - PHEV – Plug in Hybrid vehicle with ICE
- Fuel/energy carrier

[2] All possible hybrids (serial, parallel) with ICE (except PHEV) are considered within future ICE propulsion systems.

- Fossil fuels:
  - diesel (incl. different blending with biodiesel, e.g. B7)
  - petrol (incl. different blending with bioethanol, e.g. E10)
  - compressed natural gas (CNG)[3] (incl. different blending with compressed renewable gas (CRG), CRG5)
- Biofuels:
  - Biodiesel (FAME – Fatty Acid Methyl Ester)
  - Hydrated Vegetable Oil (HVO)
  - Bioethanol (EtOH)
  - Compressed Renewable Gas (CRG) from biomass gasification or fermentation (via biogas) and as E-fuel
  - FT-Diesel (Fischer-Tropsch diesel from biomass gasification and as E-fuel)
  - “crop based biofuels” from grains and oil seeds
  - “advanced biofuels” from wood, straw and residues
  - E-fuels from renewable electricity using a carbon source (CO_2 or biomass), e.g. Power to liquid (PtL), Power to Gas (PtG), Biomass&Power to Liquid (BtL), biomass&Power to Gas (BPtG)
- Electricity from
  - different renewable sources and
  - grid mix in selected countries (EU28, Austria, Germany, United Kingdom, Switzerland, Spain, Poland, Italy, Australia, Canada)
- Gaseous Hydrogen (GH_2)[4] from
  - natural gas steam reforming and
  - electrolysis with renewable electricity

* Type of primary energy
  - Oil, gas, coal, nuclear
  - Biomass: forestry, agriculture, residues
  - Wind, hydro, solar
* State of technology
  - 2019
  - 2030
  - 2050

[3] Liquefied natural gas will not be considered.
[4] Liquefied hydrogen (LH_2) will not be considered.

4.3 Selected Systems

In total 64 transportation systems with passenger vehicle were selected with the stakeholder involvement. Each transportation system is analyzed for state of technology for 2019, 2030 and 2050. The transportation systems are divided in the following 6 groups

- Fossil fuel Internal Combustion Engine Vehicle (ICEV) (incl. biofuel blending): 7 systems see Table 1
- Fossil fuel and electricity Plug In Hybrid Vehicle (PHEV): 22 systems see Table 2
- Battery Electric Vehicle (BEV): 14 systems see Table 3
- Hydrogen Fuel Cell Vehicle (HFCV): 4 systems see Table 4
- Biofuel Internal Combustion Engine Vehicle (ICEV): 5 systems see Table 5 and
- E-fuel Internal Combustion Engine Vehicle (ICEV): 12 systems see Table 6.

Table 1: Selected transportation systems with fossil fuel Internal Combustion Engine Vehicle (ICEV) (incl. biofuel blending)

#	Propulsion system	fuel/energy	Resource	State of technology	Country	Abbreviation
1	ICE	petrol	raw oil	2019/2030/2050	EU28	ICE_petrol/raw oil/2019/2030/2050/EU28
2	ICE	petrol E5	raw oil&biomass mix	2019/2030/2050	EU28	ICE_petrol E5/raw oil&biomass mix/2019/2030/2050/EU28
3	ICE	petrol E10	raw oil&biomass mix	2019/2030/2050	EU28	ICE_petrol E10/raw oil&biomass mix/2019/2030/2050/EU28
4	ICE	diesel	raw oil	2019/2030/2050	EU28	ICE_diesel/raw oil/2019/2030/2050/EU28
5	ICE	diesel B7	raw oil&biomass mix	2019/2030/2050	EU28	ICE_diesel B7/raw oil&biomass mix/2019/2030/2050/EU28
6	ICE	CNG	natural gas	2019/2030/2050	EU28	ICE_CNG/natural gas/2019/2030/2050/EU28
7	ICE	CNG CRG5	natural gas&biomass mix	2019/2030/2050	EU28	ICE_CNG CRG5/natural gas&biomass mix/2019/2030/2050/EU28

Table 2: Selected transportation systems with fossil fuel and electricity Plug In Hybrid Vehicle (PHEV)

#	Propulsion system	fuel/energy	Resource	State of technology	Country	Abbreviation
8	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	EU28	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/EU28
9	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	AT	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/AT
10	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	DE	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/DE
11	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	CH	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/CH
12	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	IT	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/IT
13	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	UK	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/UK
14	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	ES	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/ES
15	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	PT	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/PT
16	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	PL	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/PL
17	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	AUS	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/AUS
18	PHEV	petrol&el.	raw oil&electr.mix	2019/2030/2050	CA	PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/CA
19	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	EU28	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/EU28
20	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	AT	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/AT
21	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	DE	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/DE
22	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	CH	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/CH
23	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	IT	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/IT
24	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	UK	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/UK
25	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	ES	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/ES
26	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	PT	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/PT
27	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	PL	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/PL
28	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	AUS	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/AUS
29	PHEV	diesel&el.	raw oil&electr.mix	2019/2030/2050	CA	PHEV_diesel&el./raw oil&electr.mix/2019/2030/2050/CA

Table 3: Selected transportation systems with Battery Electric Vehicle (BEV):

#	Propulsion system	fuel/energy	Resource	State of technology	Country	Abbreviation
30	BEV	electricity	electr. mix	2019/2030/2050	EU28	BEV_electricity/electr. mix/2019/2030/2050/EU28
31	BEV	electricity	PV	2019/2030/2050	EU28	BEV_electricity/PV/2019/2030/2050/EU28
32	BEV	electricity	wind	2019/2030/2050	EU28	BEV_electricity/wind/2019/2030/2050/EU28
33	BEV	electricity	hydro	2019/2030/2050	EU28	BEV_electricity/hydro/2019/2030/2050/EU28
34	BEV	electricity	electr. mix	2019/2030/2050	AT	BEV_electricity/electr. mix/2019/2030/2050/AT
35	BEV	electricity	electr. mix	2019/2030/2050	DE	BEV_electricity/electr. mix/2019/2030/2050/DE
36	BEV	electricity	electr. mix	2019/2030/2050	CH	BEV_electricity/electr. mix/2019/2030/2050/CH
37	BEV	electricity	electr. mix	2019/2030/2050	IT	BEV_electricity/electr. mix/2019/2030/2050/IT
38	BEV	electricity	electr. mix	2019/2030/2050	UK	BEV_electricity/electr. mix/2019/2030/2050/UK
39	BEV	electricity	electr. mix	2019/2030/2050	ES	BEV_electricity/electr. mix/2019/2030/2050/ES
40	BEV	electricity	electr. mix	2019/2030/2050	PT	BEV_electricity/electr. mix/2019/2030/2050/PT
41	BEV	electricity	electr. mix	2019/2030/2050	PL	BEV_electricity/electr. mix/2019/2030/2050/PL
42	BEV	electricity	electr. mix	2019/2030/2050	AUS	BEV_electricity/electr. mix/2019/2030/2050/AUS
43	BEV	electricity	electr. mix	2019/2030/2050	CA	BEV_electricity/electr. mix/2019/2030/2050/CA

Table 4: Selected transportation systems with Hydrogen Fuel Cell Vehicle (HFCV)

#	Propulsion system	fuel/energy	Resource	State of technology	Country	Abbreviation
44	HFC	hydrogen	natural gas	2019/2030/2050	EU28	HFC_hydrogen/natural gas/2019/2030/2050/EU28
45	HFC	hydrogen	PV	2019/2030/2050	EU28	HFC_hydrogen/PV/2019/2030/2050/EU28
46	HFC	hydrogen	wind	2019/2030/2050	EU28	HFC_hydrogen/wind/2019/2030/2050/EU28
47	HFC	hydrogen	hydro	2019/2030/2050	EU28	HFC_hydrogen/hydro/2019/2030/2050/EU28

Table 5: Selected transportation systems with biofuel Internal Combustion Engine Vehicle (ICEV)

#	Propulsion system	fuel/energy	Resource	State of technology	Country	Abbreviation
48	ICE	FAME	biomass mix	2019/2030/2050	EU28	ICE_FAME/biomass mix/2019/2030/2050/EU28
49	ICE	HVO	biomass mix	2019/2030/2050	EU28	ICE_HVO/biomass mix/2019/2030/2050/EU28
50	ICE	EtOH	biomass mix	2019/2030/2050	EU28	ICE_EtOH/biomass mix/2019/2030/2050/EU28
51	ICE	FT diesel	straw&wood	2019/2030/2050	EU28	ICE_FT diesel/straw&wood/2019/2030/2050/EU28
52	ICE	CRG	straw&wood, biogas mix	2019/2030/2050	EU28	ICE_CRG/straw&wood, biogas mix/2019/2030/2050/EU28

Table 6: Selected transportation systems with E-fuel Internal Combustion Engine Vehicle (ICEV)

#	Propulsion system	fuel/energy	Resource	State of technology	Country	Abbreviation
53	ICE	E-fuel FT diesel	H2 wind&CO2 air	2019/2030/2050	EU28	ICE_E-fuel FT diesel/H2 wind&CO2 air/2019/2030/2050/EU28
54	ICE	E-fuel FT diesel	H2 wind&CO2 ind	2019/2030/2050	EU28	ICE_E-fuel FT diesel/H2 wind&CO2 ind/2019/2030/2050/EU28
55	ICE	E-fuel FT diesel	H2 wind&biomass	2019/2030/2050	EU28	ICE_E-fuel FT diesel/H2 wind&biomass/2019/2030/2050/EU28
56	ICE	E-fuel CRG	H2 wind&CO2 air	2019/2030/2050	EU28	ICE_E-fuel CRG/H2 wind&CO2 air/2019/2030/2050/EU28
57	ICE	E-fuel CRG	H2 wind&CO2 ind	2019/2030/2050	EU28	ICE_E-fuel CRG/H2 wind&CO2 ind/2019/2030/2050/EU28
58	ICE	E-fuel CRG	H2 wind&biomass	2019/2030/2050	EU28	ICE_E-fuel CRG/H2 wind&biomass/2019/2030/2050/EU28
59	ICE	E-fuel FT diesel	electr. mix&CO2 air	2019/2030/2050	EU28	ICE_E-fuel FT diesel/electr. mix&CO2 air/2019/2030/2050/EU28
60	ICE	E-fuel FT diesel	electr. mix&CO2 ind	2019/2030/2050	EU28	ICE_E-fuel FT diesel/electr. mix&CO2 ind/2019/2030/2050/EU28
61	ICE	E-fuel FT diesel	electr. mix&CO2 biomass	2019/2030/2050	EU28	ICE_E-fuel FT diesel/electr. mix&CO2 biomass/2019/2030/2050/EU28
62	ICE	E-fuel CRG	electr. mix&CO2 air	2019/2030/2050	EU28	ICE_E-fuel CRG/electr. mix&CO2 air/2019/2030/2050/EU28
63	ICE	E-fuel CRG	electr. mix&CO2 ind	2019/2030/2050	EU28	ICE_E-fuel CRG/electr. mix&CO2 ind/2019/2030/2050/EU28
64	ICE	E-fuel CRG	electr. mix&CO2 biomass	2019/2030/2050	EU28	ICE_E-fuel CRG/electr. mix&CO2 biomass/2019/2030/2050/EU28

4.4 Schemes of Process Chains

4.4.1 Description

The schemes of the process chain show the most relevant processes in the LCA of a transportation system from main raw material in nature (on the top) to the provided transportation service (on the bottom).

The 5 most relevant process steps are (Figure 12)

1. Cultivation, collection or extraction of raw materials
2. Transportation of raw materials
3. Conversion of raw materials to transportation fuel, where other products might be co-produced
4. Distribution of transportation fuel/energy incl. filling/charging station
5. Vehicle using the transportation fuel

The main inputs to the process steps are energy (e.g. electricity, fuels), auxiliary materials (e.g. fertilizer, chemicals) and materials for the production of the facilities; e.g. the materials for the production of the vehicle also including the battery for BEV and the energy for manufacturing and assembling.

The main outputs of a process step are beside transportation fuels, GHG emissions and co-products (e.g. animal feed, chemicals, heat).

On the top of a process step the most important input into it (e.g. raw oil, hydrogen) is shown and an arrow links the process to the previous step in the process chain. On the bottom of the process step the most important output (e.g. diesel, electricity) is shown and an arrow links the process to the next step in the process chain.

On the left hand side, the input in terms of cumulated primary energy consumption is shown, which is associated with the energy and material needed, and is calculated in the LCA.

On the right hand side, the output in terms of GHG emissions (covering CO_2, CH_4, and N_2O) is shown, which is associated with the energy and material needed, and is calculated in the LCA.

The GHG emissions cover

- direct emissions from fuel combustion in the process step
- direct emissions from processing or losses (e.g. CH_4 from natural gas extraction, N_2O from fertilization)
- indirect emissions from the supply of energy & materials and the production & end of life of the facilities

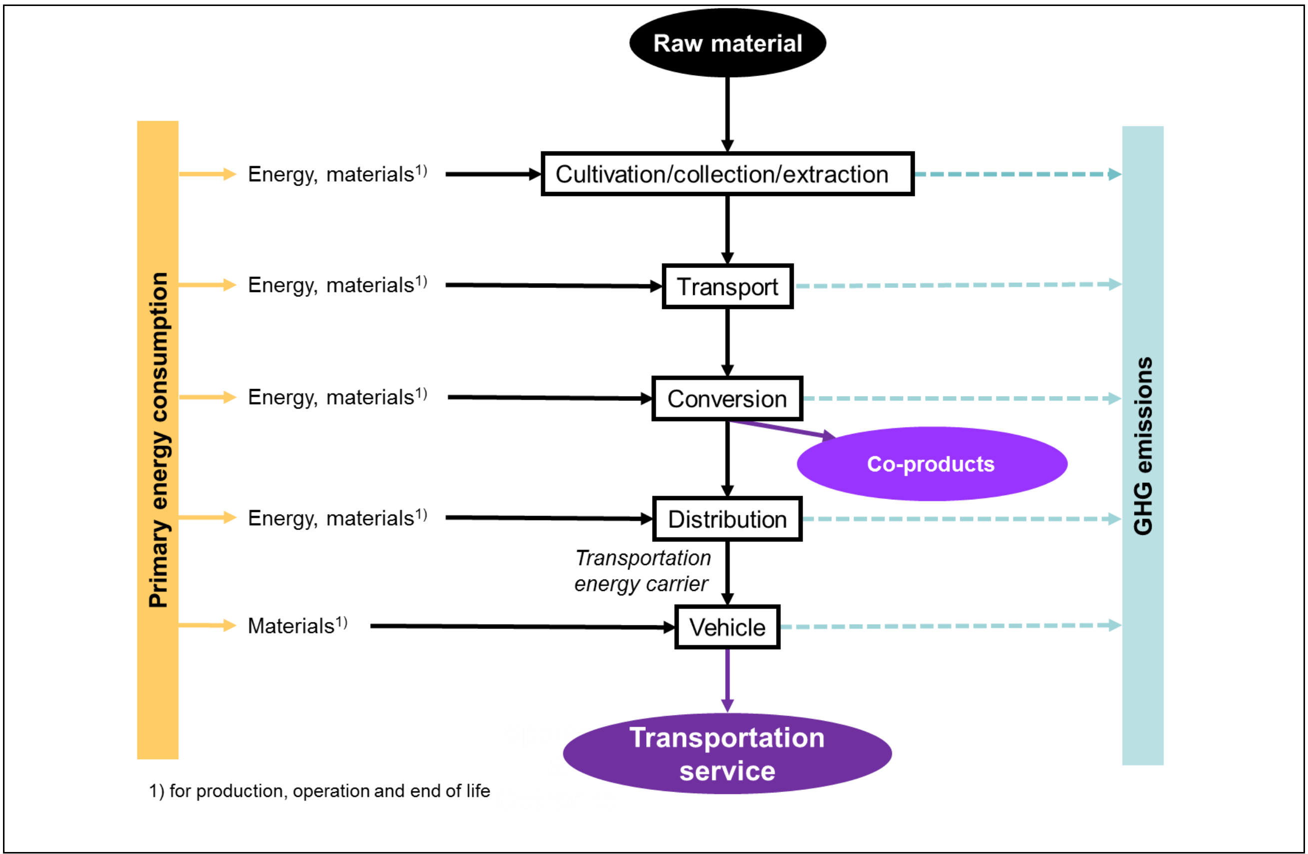


Figure 12: Generic scheme of process chain for transportation system

4.4.2 Examples

Some examples of analysed process chains are selected for a detailed description. The selected examples are representative for all 64 transportation systems, as the others are variations of the ones shown here. The 9 examples are the following, where the number (#) refers to the selected transportation systems in chapter 4.3:

1. "ICE_petrol/raw oil/2019/2030/2050/EU28" (#1)
2. "ICE_FAME/biomass mix/2019/2030/2050/EU28" (#48)
3. "ICE_diesel B7/raw oil&biomass mix/2019/2030/2050/EU28" (#5)
4. "BEV_electricity/wind/2019/2030/2050/EU28" (#32)
5. "BEV_electricity/electr. mix/2019/2030/2050/EU28" (#30)
6. "PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/EU28" (#8)

7. “HFC_hydrogen/PV/2019/2030/2050/EU28” (#45)

8. “ICE_CRG/straw&wood/2019/2030/2050/EU28” (#52)

9. “ICE_E-fuel FT diesel/H2 wind&CO2 air/2019/2030/2050/EU28” (#53)

10. “ICE_E-fuel FT diesel/electr. mix&CO2 biomass/2019/2030/2050/EU28 (#61)

In all examples the process chain is the same for the state of technology in 2019, 2030 and 2050.

In Figure 13 the process chain for “ICE_petrol/raw oil” is shown. The process chain starts with the raw oil in nature and ends with the supply of a transportation service. The raw oil is extracted, which requires energy and direct GHG emissions might occur. Then the extracted raw oil is transported to the refinery, where the raw oil is refined to various energy carriers (e.g. petrol, diesel, kerosene, LPG) and raw materials for the petro-chemical industry. The energy demand and GHG emission up to the refinery are allocated by the energy content to the various products of the refinery (“energy allocation”). Then the petrol is distributed to the filling stations, where it is used in the internal combustion engine vehicle to provide the transportation service.

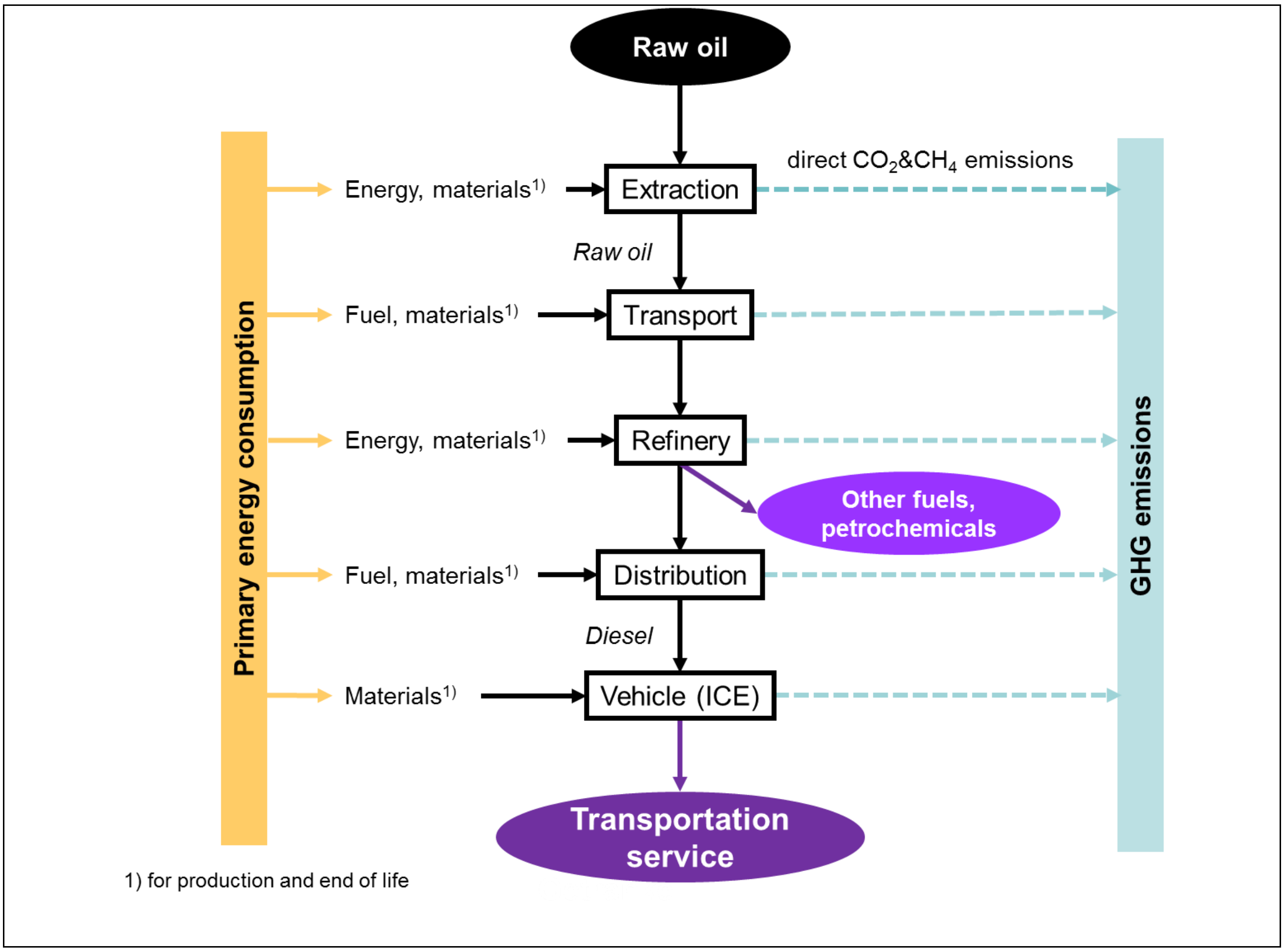


Figure 13: Process Chain for "ICE_petrol/raw oil/2019/2030/2050/EU28" (#1)

In Figure 14 the process chain for "ICE_FAME/biomass mix" is shown. The process chain starts with agricultural land and with oil and fat residues from industry or households. The chain ends with the supply of a transportation service. The oil crops are cultivated and harvested in agriculture and the residues are collected. GHG emissions derive from Nitrogen fertilisation in agriculture as direct N_2O-emissions. The straw remains on the field and is plough in, and the harvested oil crops and the collected residues are transported to the biodiesel plant. In the biodiesel plant the oil crops are pressed, where vegetable oil and animal feed is produced. The raw material mix of different oil crops and residues is defined in the foreground data (description of foreground data see chapter 5.1 and 5.3). The share of animal feed and oil produced mainly depends on the oil content of the crop, e.g. rape seed about 35%. The collected residues are cleaned up. Then the vegetable oil is transestered to FAME, using methanol as a catalyst. In this process glycerine is coproduced. The animal feed substitutes other animal feed, e.g. soy feed. The glycerine substitutes for glycerine made from natural gas. The GHG emissions and energy from these substitution effects are subtracted from transportation system. Then the FAME is distributed to the filling stations by truck, where it is used in the internal combustion engine vehicle to provide the transportation service.

In Figure 15 the process chain for "ICE_diesel B7/raw oil&biomass mix" is shown. Here the petrol is blended with 7-vol% of FAME, so this process chain is a combination of the transportation system with petrol (Figure 13) and FAME (Figure 14).

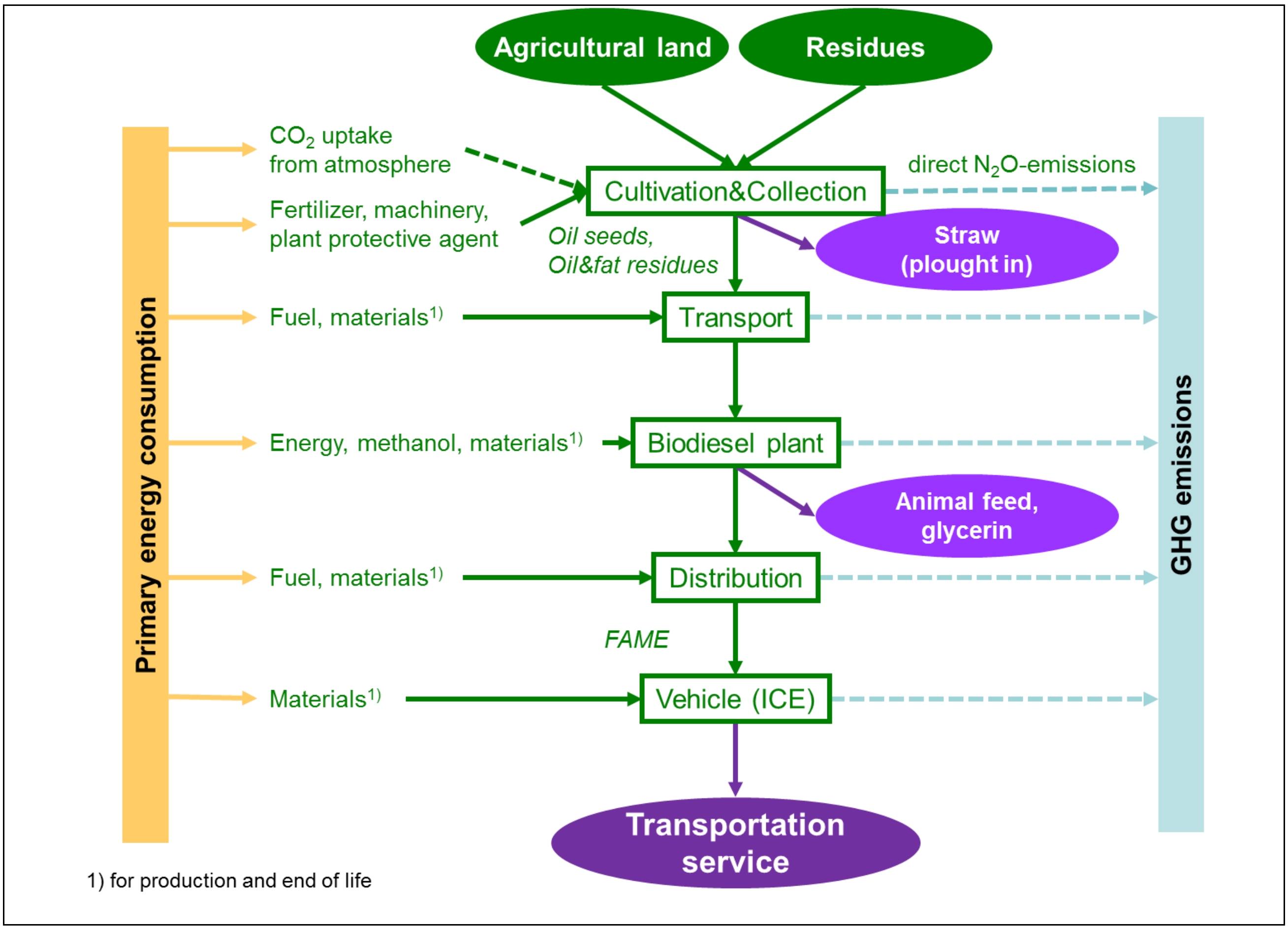


Figure 14: Process Chain for "ICE_FAME/biomass mix/2019/2030/2050/EU28" (#48)

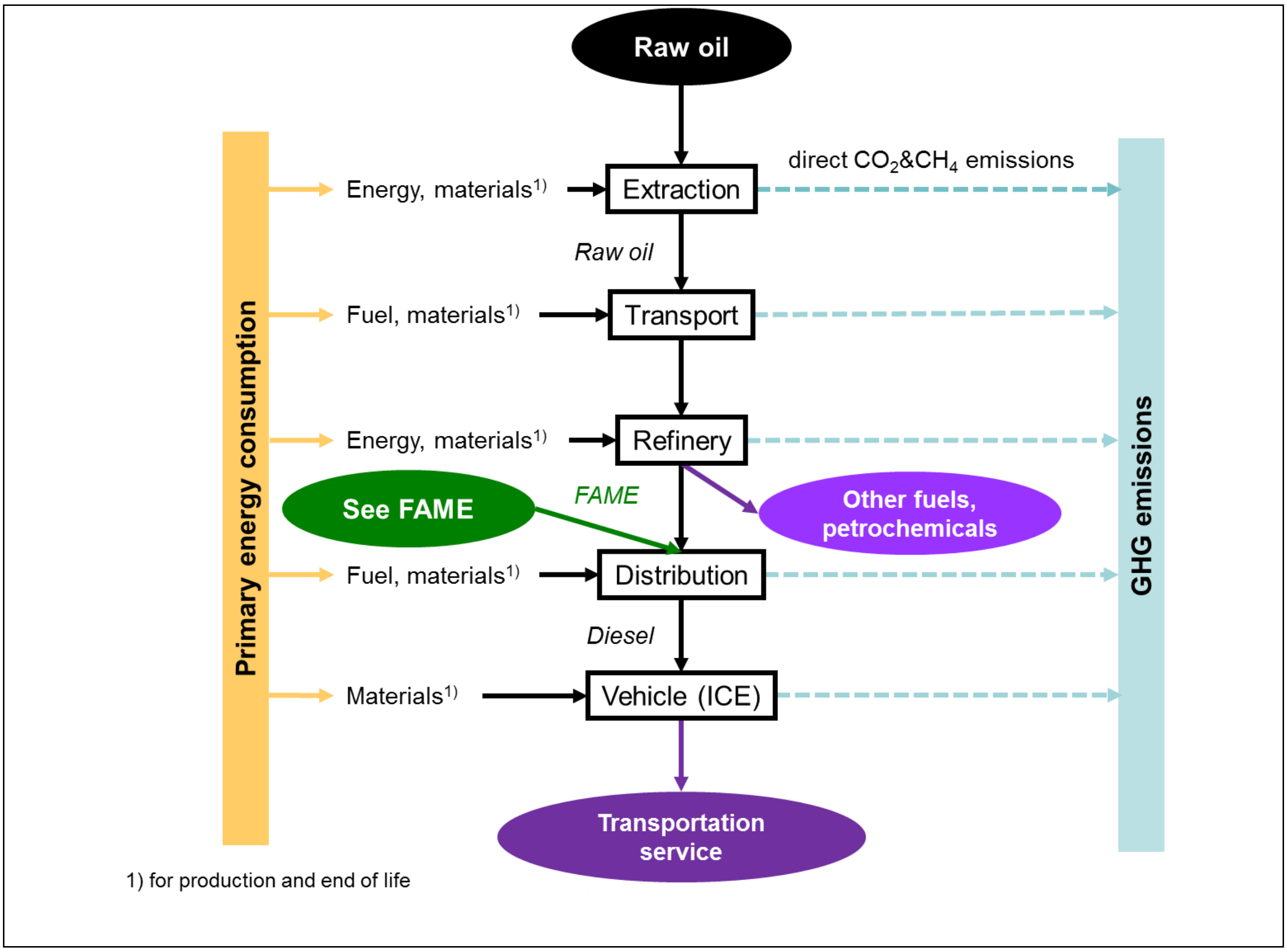


Figure 15: Process Chain for "ICE_diesel B7/raw oil&biomass mix/2019/2030/2050/EU28" (#5)

In Figure 16 the process chain for "BEV_electricity/wind" is shown. The process chain starts with the wind in nature and ends with the supply of a transportation service with a battery electric vehicle. The wind is used in a wind power plant to produce renewable electricity, which is then transported via the electricity grid to the charging station. At the charging station the electricity is brought to the battery vehicle, where it is used to provide the transportation service. If the charging time of the battery electric vehicle is very different from the time the wind power plant produces electricity, an electricity storage, e.g. pumping hydro power plant, is additionally considered.

In Figure 17 the process chain for "BEV_electricity/electr. mix" is shown. In that transportation system the electricity is produced in different power plants, using different energy carriers. If there are CHP plants in this mix, which also coproduce heat, the GHG emissions and energy are allocated due to the share electricity ("energy allocation").

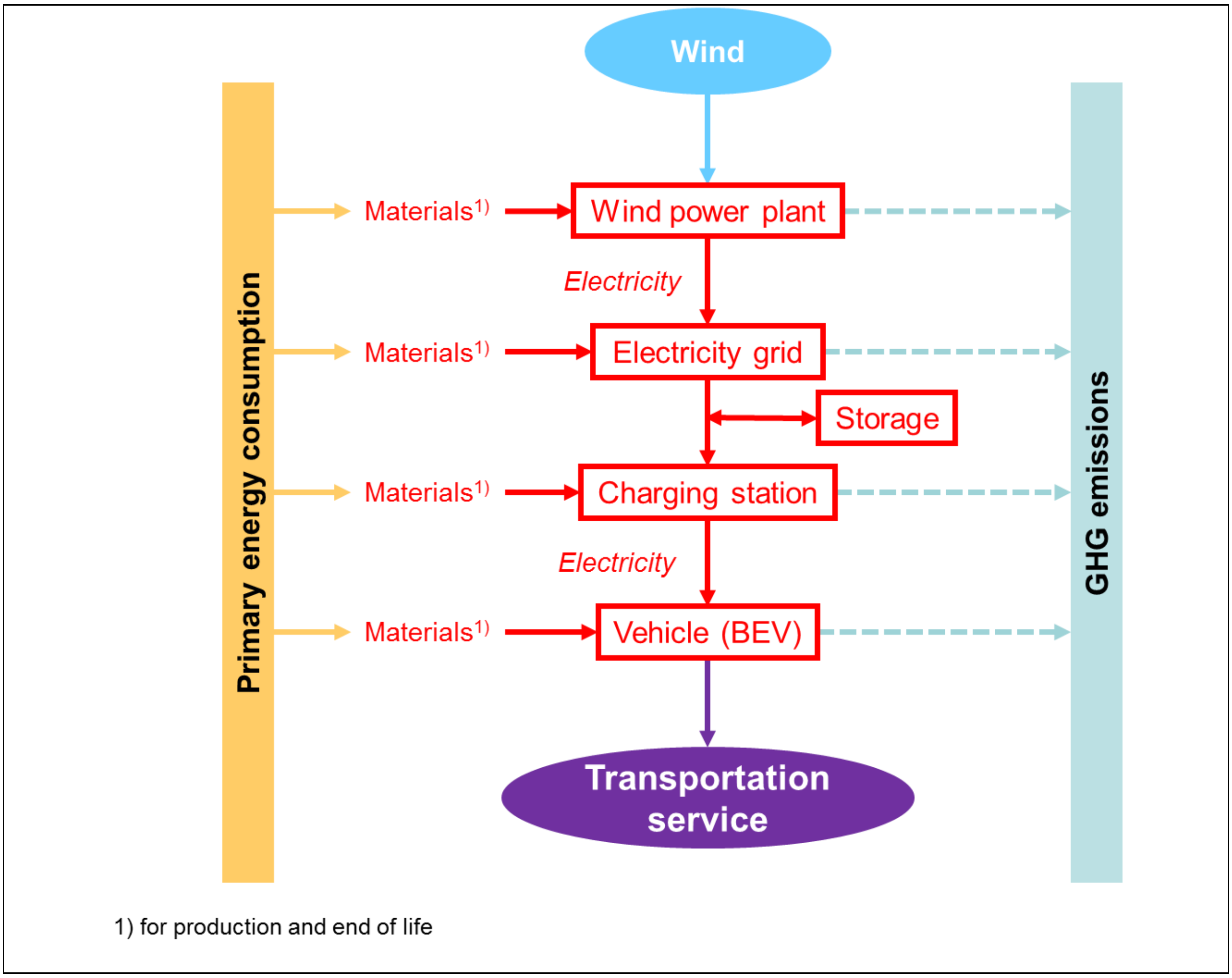


Figure 16: Process Chain for "BEV_electricity/wind/2019/2030/2050/EU28" (#32)

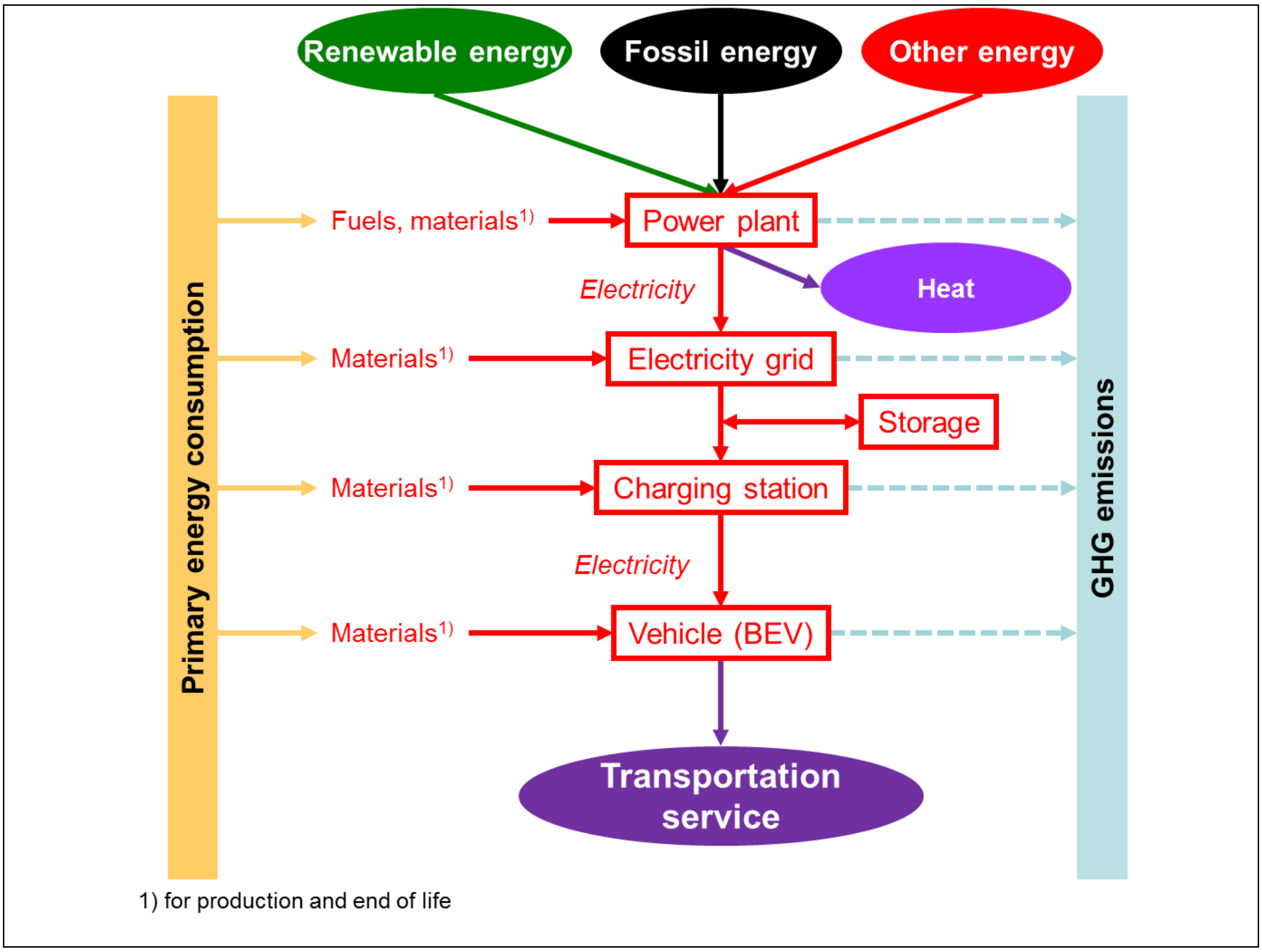


Figure 17: Process Chain for "BEV_electricity/electr. mix/2019/2030/2050/EU28" (#30)

In Figure 18 the process chain for "PHEV_petrol&el./raw oil&electr.mix" is shown, in which the transportation service is provided by a PHEV which uses petrol and grid electricity. So this process chain is a combination of the transportation system with petrol ICE vehicle (Figure 13) and the battery electric vehicle (Figure 17).

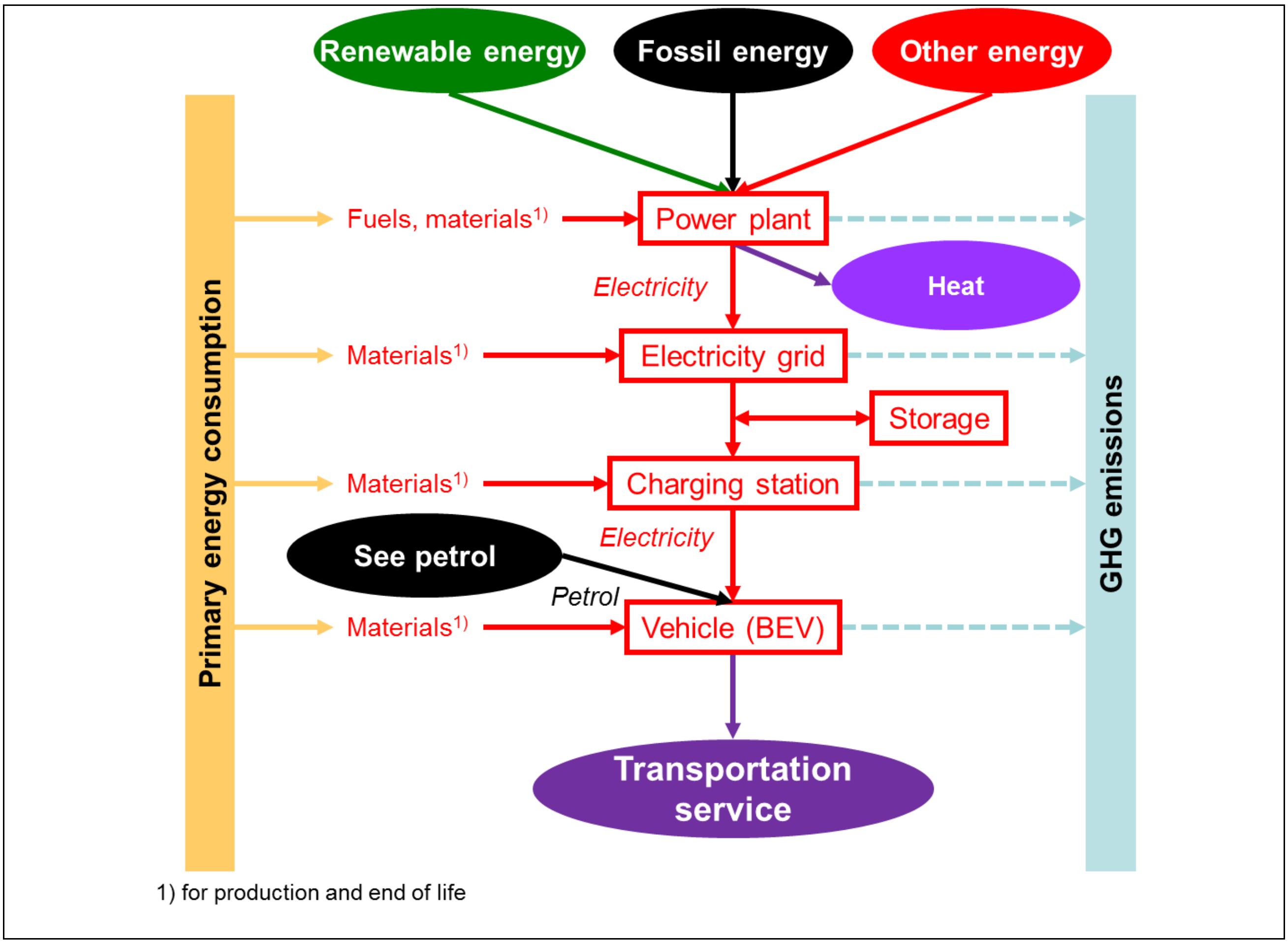


Figure 18: Process Chain for "PHEV_petrol&el./raw oil&electr.mix/2019/2030/2050/EU28" (#8)

In Figure 19 the process chain for "HFC_hydrogen/PV" is shown. The process chain starts with the solar radiation in nature and ends with the supply of a transportation service with a hydrogen fuel cell vehicle. The sun is used in a PV power plant to produce renewable electricity, which is then transported via the electricity grid to the electrolysis, where water is split into hydrogen and oxygen. The coproduced oxygen and heat from the electrolysis might be used in future. The hydrogen is stored and distributed by truck to the filling station. The gaseous hydrogen is filled in the fuel cell vehicle, which provides the transportation service.

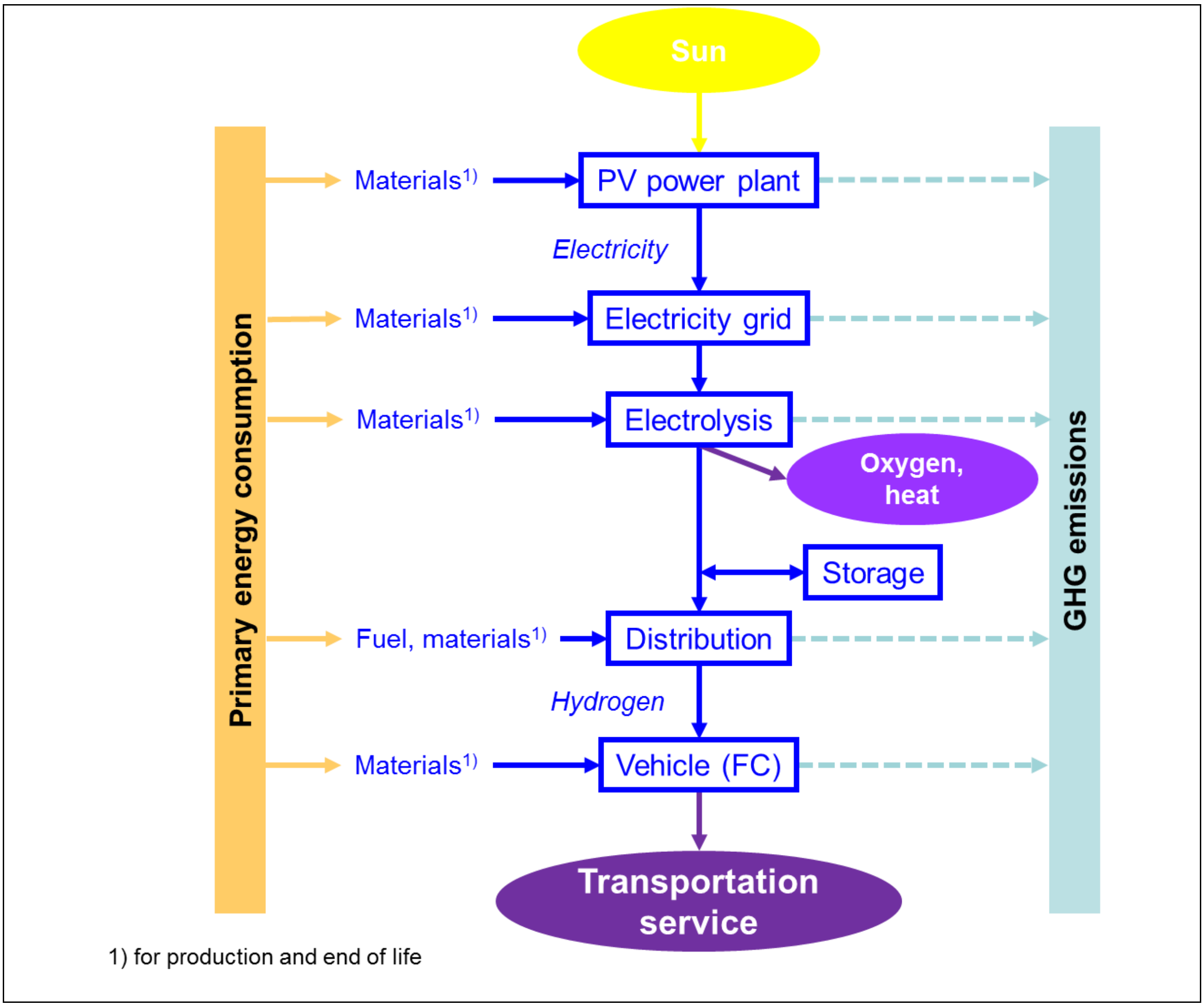


Figure 19: Process Chain for "HFC_hydrogen/PV/2019/2030/2050/EU28" (#45)

In Figure 20 the process chain for "ICE_CRG/straw&wood" is shown. The process chain starts with agricultural land and with forestry. The chain ends with the supply of a transportation service. The straw is collected after grain harvesting and the forest residues are collected after harvesting of round and industrial wood. The wood and straw are transported to the CRG plant, where a thermal gasification to methane takes place, which is then compressed. Heat is coproduced and the emissions are allocated due to the amount of methane and heat ("energy allocation"). The CRG is transported via the (natural) gas grid to the filling station, where it is used to fuel the vehicle, which provides the transportation service with an internal combustion engine.

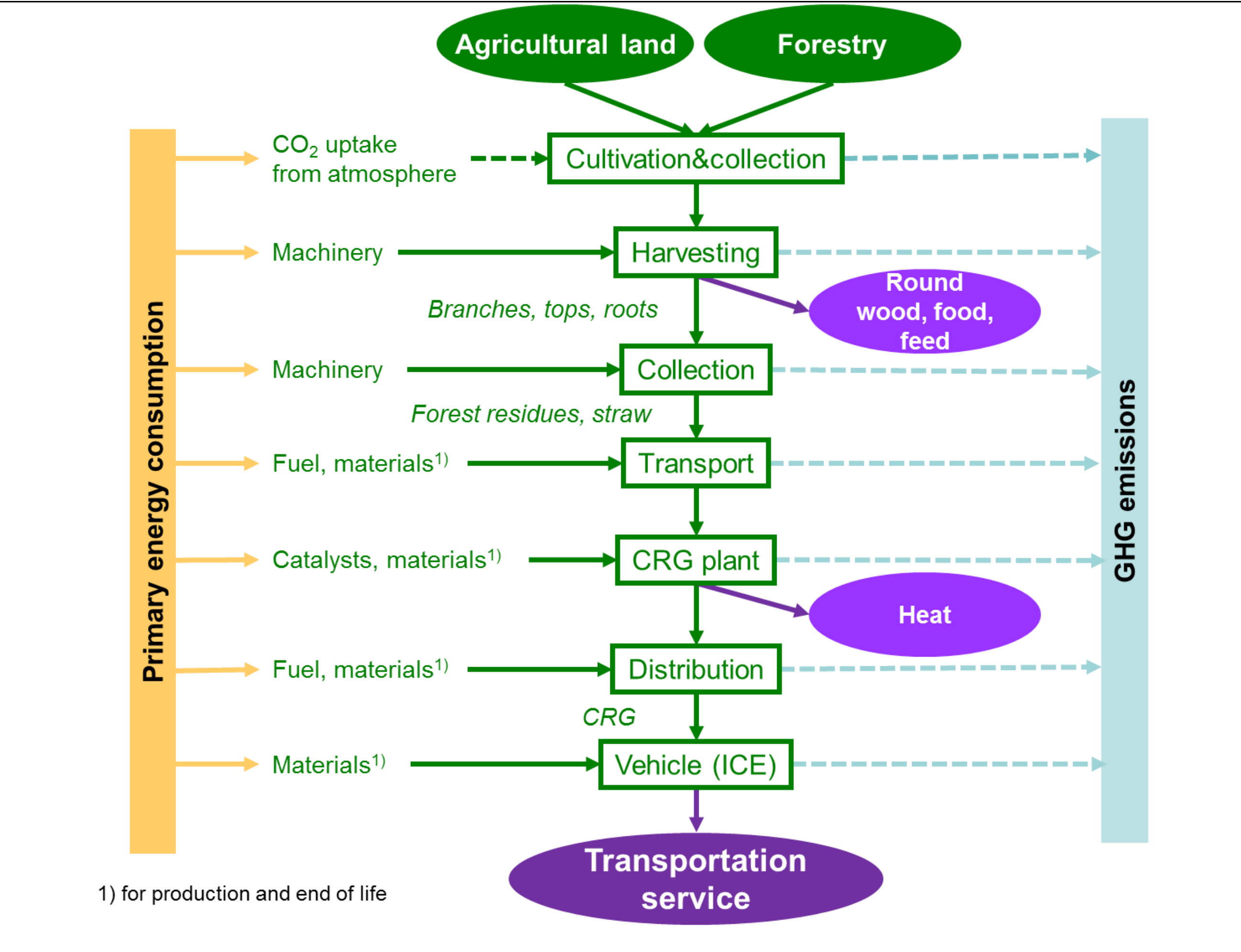


Figure 20: Process Chain for "ICE_CRG/straw&wood/2019/2030/2050/EU28" (#52)

In Figure 21 the process chain for "ICE_E-fuel FT diesel/H2 wind&CO2 air" is shown. The process chain starts with wind in nature and ends with the supply of a transportation service with an ICE vehicle. The wind power plant produces renewable electricity, which is transported to the electrolysis, where water is split into hydrogen and oxygen. The coproduced oxygen and heat from the electrolysis might be used in future, but this is not considered in the analyses here. The hydrogen is used in the FT-plant to make FT-diesel, which is similar to fossil conventional diesel, but the carbon is derived from the CO_2 in the air. In the CO_2 plant the CO_2 from the atmosphere is separated, concentrated and then used in the FT plant to produce the E-fuel FT diesel. The CO_2 plant also uses electricity from wind. The heat from the FT plant might be used for district heat, which is considered in the analysis (see chapter Annex I). The FT-diesel is distributed to the filling station by truck, where it is used to fuel the vehicle, which provides the transportation service with an internal combustion engine.

In Figure 22 the process chain for “ICE_E-fuel FT diesel/electr. mix&CO2 biomass” is shown, in which the transportation service is provided by an ICE vehicle using FT diesel. So this process chain is a combination of the transportation system with FT-diesel from biomass (like Figure 20 but FT-diesel instead of CRG) and FT using electricity and CO_2 from the air, but in this case the CO_2 comes from the biomass gasification (Figure 21).

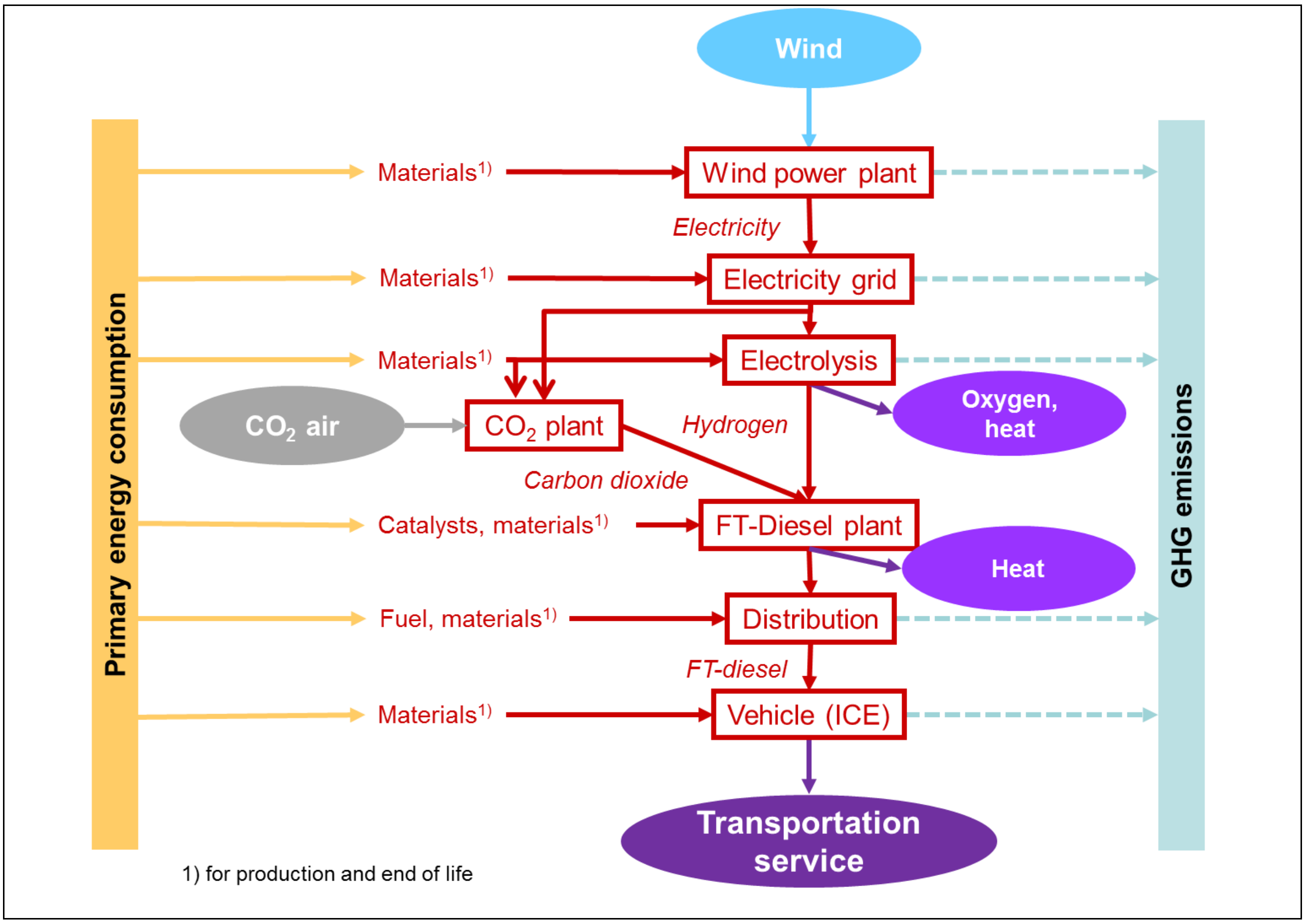


Figure 21: Process Chain for “ICE_E-fuel FT diesel/H2 wind&CO2 air/2019/2030/2050/EU28” (#53)

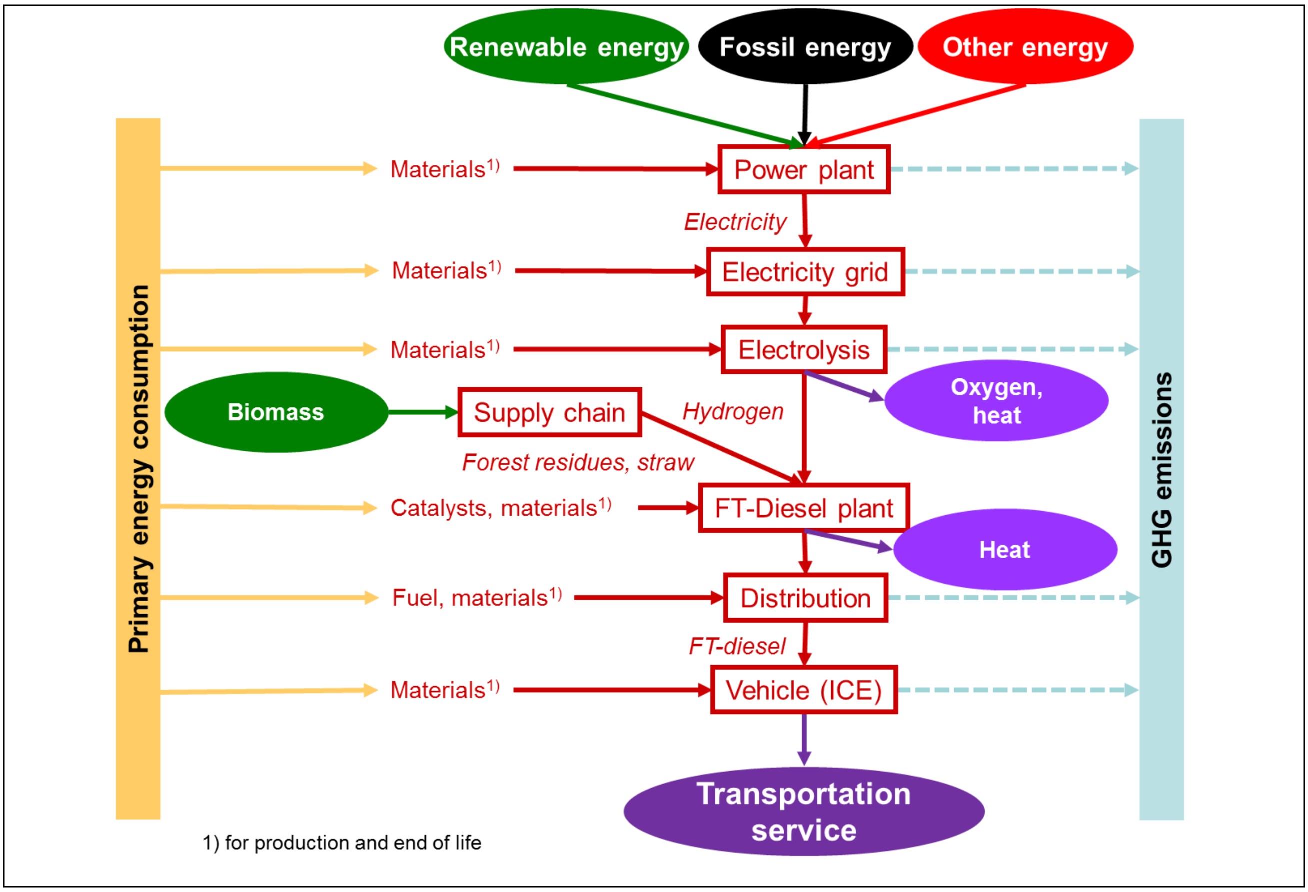


Figure 22: Process Chain for "ICE_FT diesel/electr. mix&CO2 biomass/2019/2030/2050/EU28" (#61)

5. Data Base

5.1 Data Structure

Basically in the LCA data are used that represent adequately the technical, geographical and timely framework condition to fulfil the goal and the scope of this LCA based estimation of GHG emissions and cumulated primary energy demand. As in the analyses and in the LCA TOOL the different transportation system and different states of technology (2019/2030/2050) are compared, the most important aspect of the basic data is, to reflect the most important differences (e.g. fuel consumption per km) between the systems and the states of technology to identify the most significant differences between the GHG emissions and the primary energy demand. So the main focus of the data collection and selection is to focus on the main influences that effect the estimated overall GHG emissions and primary energy demand significantly.

By reflecting this, in the LCA two different types of data categories (see example Figure 23) are set up:

- Foreground data and
- Background data.

The foreground data, which have a significant influence on the total environmental effects, the differences between the considered transportation systems and state of technologies, must be collected, assessed and documented explicitly in accordance to the goal and the scope of the LCA. Based on various literature the future trends are also own assumptions based on expert judgement and harmonisation in the stakeholder involvement. Examples for typical foreground data for the LCA are

- Vehicle: e.g. weight, energy consumption, lifetime
- Type of biomass for biofuel
- Electricity source/mix for electric vehicles

The background data, which have a minor influence on the difference between the considered environmental effects of the compared transportation systems, e.g. environmental effects of steel, are taken and documented from adequate data bases, e.g. GEMIS 2019, ecoinvent 2019. Typical background data for the LCA are on

- Electricity mix for auxiliary processes
- Production materials for vehicles
- Auxiliary material and energy for processes
- Distribution infrastructure

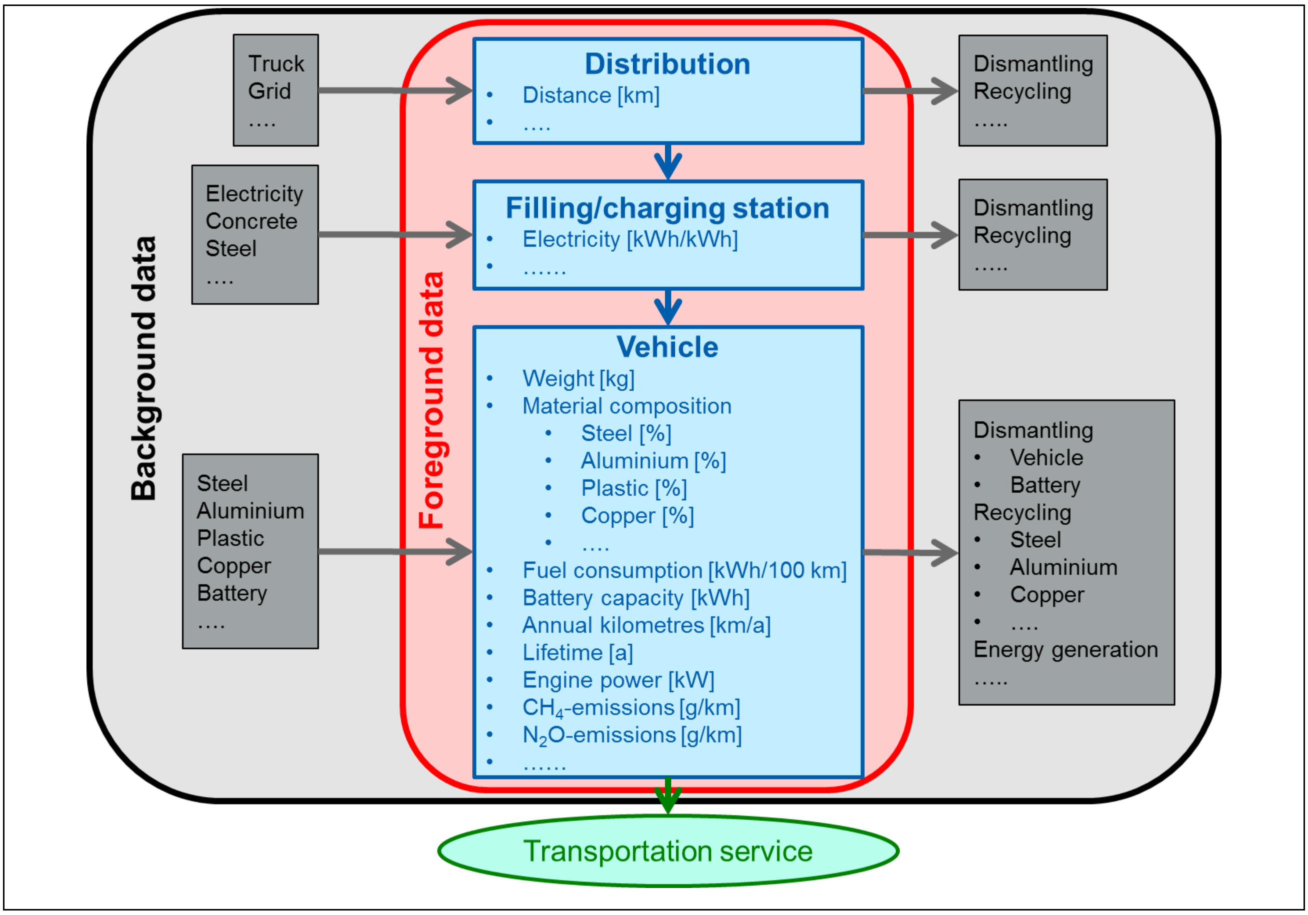


Figure 23: Examples of foreground data („Vehicle“, „Filling/charging station, “Distribution”) and background data (“Material and component production”, “Dismantling, recycling and energy generation”)

At the beginning of the LCA it is not totally clear, which data are explicitly foreground data and which are the background data, e.g. charging infrastructure for electric vehicles. The identification of all foreground data is based on one hand on the long term experience on LCA and on the other hand an iteration during the calculation of the LCA according to ISO 14,040 (see Figure 2). For this purpose also relevant inputs and clarification from the continuous stakeholder process (see chapter 3.7) as well as requirements from the future usage of the TOOL are used to finally set the foreground data explicitly.

All basic data are documented and integrated in the LCA TOOL, and the most relevant data are also given in the report. The foreground data were discussed with the stakeholders. Additionally, existing studies that were identified to be relevant for the stakeholders (e.g. FIA, ÖAMTC, ADAC), were considered in quantifying, assessing or validating the foreground data (e.g. ITF).

All foreground data can be changed by the user of the TOOL. However, for all foreground data default values are provided and reported.

5.2 Future Developments

All data are provided for the current state of technology (2019) and the possible future state for technology in 2030 and 2050.

As the future technology development cannot be analysed and assessed scientifically, the provided default data are based on expert assessment by considering the following considerations:

- The future data give a possible direction of future developments and are estimations for single data reflecting this.
- The future data are used to estimate the range of possible future GHG emissions and cumulated primary energy demand of the transportation systems to indicate "if an expected technology development takes place, e.g. improving energy consumption of vehicle, then the GHG emission and cumulated primary energy demand are the following".
- Beside the successful ongoing technology development the performance of the future technology is also depending on the time of the broad market introduction, the development of the future demand on mobility, the total energy demand, the economic development and political situation with its possible new legislations, e.g. Paris targets.
- The three main future expected technological developments are
    - The improvement of the energy efficiency in all conversion and production processes.
    - The increase of the share of renewable energy used in all production processes.
    - The broad future commercial introduction and implementation of technologies that are currently developed on pilot or demonstration scale, which are
        - Hydrogen fuel cell vehicles using renewable hydrogen
        - Lignocellulosic feedstock (e.g. wood and straw) for advanced biofuels, e.g. FT-diesel
        - E-fuels using a carbon source (e.g. biomass, CO_2 from atmosphere) and (renewable) electricity for liquid and gaseous carbon containing fuels.

    - Smart electricity grids, sector coupling, new electricity storage systems, e.g. using fluctuating electricity from PV for charging a BEV

  - Vehicle to grid option for electric vehicles to provide grid services and autonomous driving vehicles (with their additional necessary infrastructure) are excluded from the estimations of the future technological developments

One main source for this estimation of the future technology development was *"The EU Reference Scenario 2016: Energy, transport and GHG emissions – Trends to 2050"* (EU 2018) (Website: https://ec.europa.eu/energy/en/data-analysis/energy-modelling). The most relevant data of this scenario are shown in Table 7.

<u>Table 7:</u> Identified main data for the technology development and implementation in Europe (EU 2018)

	EU28				Austria				Germany			
	2015	2020	2030	2050	2015	2020	2030	2050	2015	2020	2030	2050
Gross Electricity generation by source (1) (GWhe)	3,251,309	3,357,685	3,527,528	4,063,737	59,617.65	71,620.63	79,932.76	90,574.55	- 48,203	1,942	15,833	14,973
Nuclear energy	25.8%	23.0%	22.0%	18.1%	0.0%	0.0%	0.0%	0.0%	16.2%	5.8%	0.0%	0.0%
Solids	25.2%	22.9%	16.0%	6.2%	5.9%	6.9%	4.1%	0.0%	45.5%	45.7%	38.0%	21.1%
Oil (including refinery gas)	1.0%	0.7%	0.5%	0.1%	0.3%	0.3%	0.1%	0.0%	0.2%	0.2%	0.5%	0.1%
Gas (including derived gases)	16.9%	17.3%	18.6%	20.6%	9.5%	19.7%	18.3%	19.3%	15.5%	12.5%	17.8%	19.3%
Biomass-waste	5.6%	6.3%	8.0%	9.6%	3.6%	4.9%	5.1%	7.5%	9.8%	5.7%	8.7%	11.6%
Hydro (pumping excluded)	10.8%	11.2%	10.7%	10.4%	57.3%	60.3%	55.7%	50.5%	3.7%	3.8%	3.9%	4.7%
Wind	8.2%	13.8%	17.2%	24.1%	5.5%	6.2%	12.6%	17.0%	11.0%	18.3%	21.0%	30.2%
Solar	3.1%	4.6%	6.6%	10.5%	1.2%	1.6%	4.1%	5.6%	5.8%	8.1%	9.9%	12.8%
Geothermal and other renewables	0.2%	0.3%	0.3%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	0.1%
Net import												
	20,481	17,460	2,037	-247	12,339	5,110	3,261	2,392	- 48,203	1,942	15,833	14,973
	0.6%	0.5%	0.1%	0.0%	20.7%	7.1%	4.3%	3.0%	-7.5%	0.3%	2.6%	2.5%
Power plants												
Efficiency of gross thermal power generation	40.2%	40.4%	42.2%	49.7%	40%	44%	39%	45%	41%	38%	42%	47%
% of gross electricity from CHP	12.2%	10.2%	11.8%	13.1%	18%	23%	18%	23%	13%	6%	14%	15%
% of electricity from CCS	0.0%	0.2%	0.2%	4.8%	0%	0%	0%	0%	0%	0%	0%	13%
% of carbon free (RES, nuclear) gross electricity generation	55.5%	59.2%	64.9%	73.1%	81%	73%	78%	81%	43%	42%	44%	60%
Energy efficiency												
Primary energy	1,559,892	1,526,914	1,436,069	1,367,462	30,896	31,154	30,293	29,517	297,924	282,452	251,687	229,575
Final Energy Demand	1,133,457	1,133,797	1,081,368	1,085,865	28,425	28,027	27,082	26,942	217,308	212,550	197,367	185,668
Change primary energy	2.2%	0.0%	-5.9%	-10.4%	-1%	0%	-3%	-5%	5%	0%	-11%	-19%
Change final enrgy	0.0%	0.0%	-4.6%	-4.2%	1%	0%	-3%	-4%	2%	0%	-7%	-13%
Energy intensity indicators												
Gross Inl. Cons./GDP (toe/M€13)	154	113	93	66	113	97	82	59	144	104	86	66
Industry (Energy on Value added, index 2000=100)	100	75	62	47	100	104	89	68	100	90	77	61
Residential (Energy on Private Income, index 2000=100)	100	79	66	48	100	76	63	44	100	75	64	51
Tertiary (Energy on Value added, index 2000=100)	100	83	69	51	100	76	66	49	100	76	64	49
Passenger transport (toe/Mpkm) (6)	39	30	25	21	47	37	31	27	42	28	23	19
Freight transport	33	30	28	25	30	41	36	31	27	20	18	16
averge (calculated)	*88*	*68*	*57*	*43*	*82*	*72*	*61*	*46*	*86*	*65*	*55*	*44*
Change 2020/2030/2050			*-17%*	*-24%*			*-15%*	*-24%*			*-16%*	*-21%*
Share renewables												
RES in Gross Final Energy Consumption (7) (in%)	7.5%	8.7%	12.4%	16.1%	24.6%	23.6%	30.5%	34.5%	3.6%	6.7%	10.5%	13.5%
RES-H&C share	9.0%	10.3%	14.0%	17.4%	20.4%	22.0%	29.7%	37.0%	4.2%	6.7%	9.6%	10.6%
RES-E share	13.3%	14.8%	19.7%	28.2%	66.9%	62.4%	65.7%	68.0%	6.1%	10.5%	18.1%	29.5%
RES-T share (based on ILUC formula)	0.9%	1.7%	5.2%	6.9%	6.8%	4.8%	10.9%	11.4%	0.8%	4.2%	6.9%	8.8%
averge (calculated)	*7.7%*	*8.9%*	*12.8%*	*17.2%*	*29.7%*	*28.2%*	*34.2%*	*37.7%*	*3.7%*	*7.0%*	*11.3%*	*15.6%*
Change 2020/2030/2050			*44%*	*34%*			*21%*	*10%*			*60%*	*38%*

	Italy				Poland				Portugal			
	2015	2020	2030	2050	2015	2020	2030	2050	2015	2020	2030	2050
Gross Electricity generation by source (1) (GWhe)	288,972	316,523	323,149	417,853	162,367	176,244	203,166	245,347	50,199	48,507	48,243	52,086
Nuclear energy	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	28.2%	0.0%	0.0%	0.0%	0.0%
Solids	18.6%	21.2%	13.8%	0.0%	78.1%	80.1%	65.0%	25.9%	30.6%	7.3%	0.0%	0.0%
Oil (including refinery gas)	2.8%	2.5%	2.4%	0.2%	0.0%	0.0%	0.2%	0.1%	1.6%	4.1%	2.7%	0.9%
Gas (including derived gases)	34.8%	39.9%	37.9%	34.4%	1.7%	5.5%	14.9%	17.0%	19.6%	17.8%	10.7%	2.6%
Biomass-waste	5.9%	6.8%	7.9%	15.2%	5.5%	6.5%	7.8%	8.5%	6.1%	6.3%	6.0%	7.7%
Hydro (pumping excluded)	15.2%	15.0%	15.4%	12.9%	1.4%	1.4%	1.4%	1.8%	19.7%	38.2%	39.1%	36.7%
Wind	4.6%	4.6%	10.1%	14.8%	5.5%	6.5%	10.7%	18.3%	24.1%	24.3%	32.3%	36.9%
Solar	7.4%	8.1%	10.5%	21.0%	0.0%	0.0%	0.0%	0.1%	1.4%	1.6%	8.8%	14.7%
Geothermal and other renewables	2.0%	2.0%	1.9%	1.4%	0.0%	0.0%	0.0%	0.0%	0.4%	0.4%	0.4%	0.4%
Net import												
	45,981	29,983	30,755	19,499	70.4	735.2	1356.6	1479.1	2,265	5,240	5,138	3,939
	15.9%	9.5%	9.8%	6.0%	0.0%	0.4%	0.7%	0.7%	4.5%	10.8%	10.7%	8.2%
Power plants												
Efficiency of gross thermal power generation	45%	46%	47%	55%	35%	37%	39%	43%	42%	44%	39%	36%
% of gross electricity from CHP	15%	15%	11%	7%	18%	21%	19%	24%	17%	23%	19%	11%
% of electricity from CCS	0%	0%	0%	0%	0%	0%	0%	21%	0%	0%	0%	0%
% of carbon free (RES, nuclear) gross electricity generation	38%	36%	46%	65%	13%	14%	20%	57%	50%	71%	87%	96%
Energy efficiency												
Primary energy	151,986	153,883	142,394	136,887	96,389	98,982	99,307	101,337	21,514	19,893	18,515	17,354
Final Energy Demand	122,385	122,484	115,857	116,607	68,144	71,659	72,935	74,647	16,789	16,831	16,266	15,574
Change primary energy	-1%	0%	-7%	-11%	-3%	0%	0%	2%	8%	0%	-7%	-13%
Change final enrgy	0%	0%	-5%	-5%	-5%	0%	2%	4%	0%	0%	-3%	-7%
Energy intensity indicators												
Gross Inl. Cons./GDP (toe/M€13)	111	96	79	57	350	214	171	138	150	114	92	73
Industry (Energy on Value added, index 2000=100)	100	78	62	49	100	32	25	18	100	83	67	52
Residential (Energy on Private Income, index 2000=100)	100	114	99	70	100	66	51	40	100	85	73	60
Tertiary (Energy on Value added, index 2000=100)	100	113	97	75	100	76	61	48	100	85	70	59
Passenger transport (toe/Mpkm) (6)	33	26	23	20	32	34	28	24	48	37	32	27
Freight transport	35	33	31	29	22	34	29	27	36	31	28	26
averge (calculated)	*80*	*77*	*65*	*50*	*117*	*76*	*61*	*49*	*89*	*73*	*60*	*50*
Change 2020/2030/2050			*-15%*	*-23%*			*-20%*	*-19%*			*-17%*	*-18%*
Share renewables												
RES in Gross Final Energy Consumption (7) (in%)	4.7%	5.8%	10.5%	18.2%	6.5%	6.9%	9.2%	11.8%	19.1%	19.4%	24.3%	25.3%
RES-H&C share	2.9%	4.6%	10.4%	20.1%	9.6%	10.2%	11.6%	13.8%	30.4%	32.1%	33.9%	36.8%
RES-E share	15.7%	16.3%	20.1%	33.6%	1.6%	2.7%	6.6%	13.4%	28.3%	27.7%	40.7%	47.4%
RES-T share (based on ILUC formula)	0.6%	1.1%	5.0%	7.1%	0.2%	0.7%	6.1%	7.5%	0.4%	0.4%	5.7%	1.3%
averge (calculated)	*5.9%*	*6.9%*	*11.5%*	*19.7%*	*4.5%*	*5.1%*	*8.4%*	*11.6%*	*19.5%*	*19.9%*	*26.1%*	*27.7%*
Change 2020/2030/2050			*66%*	*72%*			*64%*	*38%*			*31%*	*6%*

	Spain				United Kingdom			
	2015	2020	2030	2050	2015	2020	2030	2050
Gross Electricity generation by source (1) (GWhe)	275,295.3	282,996.3	287,052.2	328,449.0	357,131	369,460	398,021	497,924
Nuclear energy	20.5%	20.5%	20.0%	0.0%	17.5%	17.0%	26.9%	29.1%
Solids	20.4%	19.9%	5.3%	0.2%	26.1%	7.2%	0.9%	0.7%
Oil (including refinery gas)	1.8%	0.2%	0.6%	0.5%	1.2%	0.9%	0.7%	0.1%
Gas (including derived gases)	18.8%	19.9%	17.4%	13.5%	31.8%	31.3%	27.2%	29.7%
Biomass-waste	1.6%	2.1%	3.1%	3.8%	7.1%	13.8%	16.6%	11.1%
Hydro (pumping excluded)	11.7%	11.8%	11.7%	10.6%	1.5%	1.5%	1.4%	1.1%
Wind	18.3%	19.9%	25.1%	38.9%	9.3%	25.8%	24.0%	26.2%
Solar	4.3%	5.7%	16.8%	32.6%	2.1%	2.4%	2.3%	1.9%
Geothermal and other renewables	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%
Net import								
	- 1,327	4,415	4,671	- 4,374	18,380	15,594	12,362	5,480
	-0.5%	1.6%	1.7%	-1.5%	5.1%	4.2%	3.3%	1.4%
Power plants								
Efficiency of gross thermal power generation	43%	43%	44%	53%	41%	45%	47%	61%
% of gross electricity from CHP	10%	5%	6%	8%	5%	5%	5%	4%
% of electricity from CCS	0%	0%	0%	0%	0%	1%	2%	1%
% of carbon free (RES, nuclear) gross electricity generation	58%	60%	77%	86%	39%	61%	71%	70%
Energy efficiency								
Primary energy	118,838	118,764	108,350	97,112	191,181	176,613	168,127	169,699
Final Energy Demand	85,314	86,213	83,134	85,940	138,484	135,118	126,704	131,825
Change primary energy	0%	0%	-9%	-18%	8%	0%	-5%	-4%
Change final enrgy	-1%	0%	-4%	0%	2%	0%	-6%	-2%
Energy intensity indicators								
Gross Inl. Cons./GDP (toe/M€13)	139	103	79	56	150	88	73	50
Industry (Energy on Value added, index 2000=100)	100	83	67	50	100	68	52	39
Residential (Energy on Private Income, index 2000=100)	100	93	72	57	100	68	58	42
Tertiary (Energy on Value added, index 2000=100)	100	100	76	61	100	66	56	38
Passenger transport (toe/Mpkm) (6)	47	34	29	25	38	29	24	20
Freight transport	44	39	36	34	46	42	39	36
averge (calculated)	*88*	*76*	*60*	*47*	*89*	*60*	*50*	*37*
Change 2020/2030/2050			*-21%*	*-21%*			*-16%*	*-26%*
Share renewables								
RES in Gross Final Energy Consumption (7) (in%)	8.1%	8.4%	13.8%	15.4%	0.9%	1.4%	3.3%	6.9%
RES-H&C share	11.0%	9.4%	12.6%	16.1%	0.8%	0.8%	1.8%	3.4%
RES-E share	16.6%	19.1%	29.8%	36.9%	2.6%	4.1%	7.4%	19.3%
RES-T share (based on ILUC formula)	0.6%	1.3%	5.1%	0.8%	0.1%	0.2%	3.0%	6.0%
averge (calculated)	*9.1%*	*9.6%*	*15.3%*	*17.3%*	*1.1%*	*1.6%*	*3.9%*	*8.9%*
Change 2020/2030/2050			*60%*	*13%*			*135%*	*131%*

Taking these considerations into account the following guiding principles for the expert estimation of the future state of technology for the foreground data are used:

- Vehicle technology (for all technologies)
  - Weight of vehicle:
    - 2030: 0% reduction referring to 2019
    - 2050: 30% reduction referring to 2030
  - Driving energy demand:
    - 2030: 10% reduction referring to 2019
    - 2050: 20% reduction referring to 2030
  - Energy demand for heating and cooling:
    - 2030: 10% reduction referring to 2019
    - 2050: 10% reduction referring to 2030
  - Energy demand for auxiliary in the vehicle: no change
- Raw materials mix for biofuels:
  - Biodiesel (FAME – Fatty Acid Methyl Ester) and Hydrated Vegetable Oil (HVO) the same in 2030 and 2050 as in 2019
  - Bioethanol (EtOH):
    - 2030: 10% from wood and straw reducing other feedstocks proportionally
    - 2050: 25% from wood and straw reducing other feedstocks proportionally
  - Compressed Renewable Gas (CRG) from biomass gasification
    - 2030: 10% from wood and straw reducing other feedstocks proportionally
    - 2050: 25% from wood and straw reducing other feedstocks proportionally

    - Recycling of vehicles (except battery): no changes
- Electricity mix
    - European countries based on Trends 2050 (see Table 7)
    - Switzerland based on PSI-Report “Switzerland Energy Transition Scenarios – Development and Application of the Swiss TIMES Energy System Model (STEM)” (PSI 2014)
    - Australia based on “Future Energy Scenario” (National Grid 2018)
    - Canada based on “Canada´s Energy Future 2018 – Energy Supply and Demand Projections 2040” (National Energy Board 2018)

The estimated data for the background data in 2030 and 2050 are described and shown in chapter 5.3.5.

5.3 Foreground Data

There are three groups of foreground data specified:

1. Specification of the vehicle
2. Resources used to produce the energy carrier for the vehicle
3. Possible future developments

5.3.1 Vehicle Specification

The foreground data for the specification of the vehicle are (further details see also Annex I):

- Vehicle data (Table 8, Table 9 and Table 10)
    - Weight [kg]
    - Annual kilometres [km/a]
    - Lifetime [a]
        - Vehicle
        - Fuel cell
        - Battery

- Energy consumption [kWh/km] for
    - Driving
    - Heating
    - Cooling
    - Others
- Battery and charging (Table 11)
  - Capacity [kWh]
  - Lifetime [a]
  - Share of charging type [%]
    - Slow charging
    - Fast charging
  - Charging losses [%] (based on considerations in chapter 10.7)
    - Slow charging
    - Fast charging
  - Location of battery production [%] (based on Ajanovic et al. 2018)
    - Asia
    - Europe
    - America
  - End of life [%]
    - Material recycling
    - 2nd stationary life

Table 8: Foreground data for vehicles with ICE using fossil fuels (same for all considered countries) (JOANNEUM RESEARC 2019)

Propulsion Fuel/energy		**ICE petrol**			**ICE petrol E5**			**ICE petrol E10**			**ICE diesel**			**ICE diesel B7**			**ICE CNG**		
State of technology		2019	2030	2050	2019	2030	2050	2019	2030	2050	2019	2030	2050	2019	2030	2050	2019	2030	2050
Weight	[kg]	1,180	1,180	820	1,180	1,180	820	1,180	1,180	820	1,260	1,260	880	1,260	1,260	880	1,190	1,190	830
Annual kilometres	[km/a]	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000
Lifetime	[a]	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Battery																			
capacity	[kWh]	1.3	1.6	2.0	1.3	1.6	2.0	1.3	1.6	2.0	1.3	1.6	2.0	1.3	1.6	2.0	1.3	1.6	2.0
lifetime	[a]	8.0	12.0	12.0	8.0	12.0	12.0	8.0	12.0	12.0	8.0	12.0	12.0	8.0	12.0	12.0	8.0	12.0	12.0
weight	[kg]	25	29	33	25	29	33	25	29	33	25	29	33	25	29	33	25	29	33
Energy consumption																			
driving	[kWh/100 km]	0.54	0.49	0.39	0.54	0.49	0.39	0.54	0.49	0.39	0.44	0.40	0.32	0.44	0.40	0.32	0.55	0.50	0.40
heating	[kWh/100 km]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cooling	[kWh/100 km]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
other	[kWh/100 km]	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
total	[kWh/100 km]	0.62	0.56	0.47	0.62	0.56	0.47	0.62	0.56	0.47	0.52	0.47	0.39	0.52	0.47	0.39	0.63	0.57	0.47
Emissions																			
CO_2	[g/km]	164	149	123	159	145	119	154	140	116	137	125	103	128	117	97	127	116	95
CH_4	[mg/km]	0.7	0.7	0.6	0.7	0.7	0.6	0.7	0.7	0.6	0.2	0.1	0.1	0.2	0.1	0.1	16.1	14.7	12.1
N_2O	[mg/km]	0.4	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.3	4.7	4.3	3.5	4.7	4.3	3.5	0.4	0.4	0.3
CO_2-eq	[g/km]	164	150	123	159	145	119	154	140	116	138	126	104	130	118	98	128	116	96

Table 9: Foreground data for vehicles with ICE using renewable fuels (same for all considered countries) (JOANNEUM RESEARC 2019)

Propulsion		**ICE**			**ICE**			**ICE**			**ICE**			**ICE**			**ICE**		
Fuel/energy		**CNG CRG5**			**FAME**			**HVO**			**EtOH**			**FT-diesel**			**CRG**		
State of technology		2019	2030	2050	2019	2030	2050	2019	2030	2050	2019	2030	2050	2019	2030	2050	2019	2030	2050
Weight	[kg]	1,190	1,190	830	1,260	1,260	880	1,260	1,260	880	1,180	1,180	820	1,260	1,260	880	1,190	1,190	830
Annual kilometres	[km/a]	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000
Lifetime	[a]	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Battery																			
capacity	[kWh]	1.3	1.6	2.0	1.3	1.6	2.0	1.3	1.6	2.0	1.3	1.6	2.0	1.3	1.6	2.0	1.3	1.6	2.0
lifetime	[a]	8.0	12.0	12.0	8.0	12.0	12.0	8.0	12.0	12.0	8.0	12.0	12.0	8.0	12.0	12.0	8.0	12.0	12.0
weight	[kg]	25	29	33	25	29	33	25	29	33	25	29	33	25	29	33	25	29	33
Energy consumption																			
driving	[kWh/100 km]	0.55	0.50	0.40	0.44	0.40	0.32	0.44	0.40	0.32	0.54	0.49	0.39	0.44	0.40	0.32	0.55	0.50	0.40
heating	[kWh/100 km]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cooling	[kWh/100 km]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
other	[kWh/100 km]	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
total	[kWh/100 km]	0.63	0.57	0.47	0.52	0.47	0.39	0.52	0.47	0.39	0.62	0.56	0.47	0.52	0.47	0.39	0.63	0.57	0.47
Emissions																			
CO_2	[g/km]	121	110	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CH_4	[mg/km]	16.1	14.7	12.1	0.1	0.1	0.1	0.2	0.1	0.1	0.7	0.7	0.6	0.2	0.1	0.1	16.1	14.7	12.1
N_2O	[mg/km]	0.4	0.4	0.3	5.6	5.1	4.2	4.7	4.3	3.5	0.4	0.4	0.3	4.7	4.3	3.5	0.4	0.4	0.3
CO_2-eq	[g/km]	121	110	91	1.7	1.5	1.3	1.4	1.3	1.1	0.2	0.1	0.1	1.4	1.3	1.1	0.7	0.6	0.5

Table 10: Foreground data for vehicles with PHEV, BEV and FCHV (same for all considered countries) (JOANNEUM RESEARC 2019)

Propulsion Fuel/energy		PHEV petrol&el			PHEV diesel&el			BEV electr.			FCHV hydrogen		
State of technology		2019	2030	2050	2019	2030	2050	2019	2030	2050	2019	2030	2050
Weight	[kg]	1.400	1.400	980	1.480	1.480	1.040	1.430	1.430	1.000	1.390	1.390	970
Annual kilon	[km/a]	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000
Lifetime	[a]	12	12	12	12	12	12	12	12	12	12	12	12
Battery													
capacity	[kWh]	10	12	15	10	12	15	35	45	60	1.3	2.0	5.0
lifetime	[a]	8	12	12	8	12	12	8	12	12	8	12	12
weight	[kg]	124	136	155	124	136	155	318	372	451	16	23	52
Energy consumption													
driving	[kWh/100 km]	0.29	0.26	0.21	0.26	0.23	0.19	0.09	0.08	0.06	0.24	0.22	0.06
heating	[kWh/100 km]	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.02
cooling	[kWh/100 km]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
other	[kWh/100 km]	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
total	[kWh/100 km]	0.37	0.34	0.29	0.34	0.31	0.26	0.19	0.18	0.16	0.34	0.31	0.16
id electricity	[kWh/100 km]	0.11	0.10	0.08	0.11	0.10	0.08	0.19	0.18	0.16	-	-	-
fuel	[kWh/100 km]	0.26	0.24	0.20	0.23	0.21	0.18	-	-	-	-	-	-
Emissions													
CO2	[g/km]	75	69	58	66	61	52	0	0	0	0	0	0
CH4	[mg/km]	0.6	0.5	0.5	0.1	0.1	0.1	0	0	0	0	0	0
N2O	[mg/km]	0.3	0.3	0.2	2.8	2.6	2.2	0	0	0	0	0	0
CO2-eq	[g/km]	75	69	58	128	118	101	0	0	0	0	0	0

Table 11: Foreground data for battery production, charging and end of life (own assumptions and location of battery production based on Ajanovic et al. 2018)

State of technology	2019	2030	2050
Share of charging type			
Slow charging (of km/a)	90%	70%	60%
Quick charging (of km/a)	10%	30%	40%
Charging losses			
slow charging	10%	8%	6%
quick charging	20%	16%	12%
Location of battery production			
Asia	75%	60%	45%
Europe	6%	15%	25%
America	19%	25%	30%
End of life			
recycling rate	97%	95%	95%
2nd stationary life	3%	5%	5%

5.3.2 Fossil Resources

The foreground data for the fossil resources to produce and supply the energy carrier for the vehicle are:

- Share of fossil resources (Table 12)
  - Oil
    - Conventional raw oil
    - Oil sands
  - Natural gas
    - Conventional
    - Fracking

Table 12: Foreground data for share of fossil resources for oil and gas (own assumptions)

Share of fossil resources		2019	2030	2050
Oil				
	oil sand	0%	2%	20%
	conventional	100%	98%	80%
Natural gas				
	fracking	0%	2%	20%
	conventional	100%	98%	80%

5.3.3 Biomass Resources

The foreground data for the biogenic resources to produce and supply the energy carrier for the vehicle are:

- Land use change (LUC) (Table 13), where in the default values a land use change of 10% is assumed
    - Sugar cane from pasture
    - Soy beans from pasture
    - Palm oil from tropical forest
- Share of biofuel blending
    - Biodiesel (FAME) in diesel: 7 vol.-%
    - HVO in diesel: 0 vol.-%
    - FT-diesel in diesel: 0 vol.-%
    - Bioethanol (EtOH) in petrol: 5 vol.-%
    - Renewable gas (CRG) in compressed natural gas (CNG): 5 vol.-%
- Biomass mix (Table 14) (EEA 2018, UFOP 2018, ePURE 2018 and own assumptions))
    - FAME
        - Rape seed oil
        - Cooking oil and animal fat
        - Palm oil
        - Soya oil

- HVO
  - Rape seed oil
  - Cooking oil and animal fat
  - Palm oil
  - Soya oil
- EtOH
  - Wheat and maize
  - Sugar beet
  - Sugar cane
  - Wood
  - Straw
- FT-diesel
  - Wood
  - Straw
- CRG from gasification:
  - Wood
  - Straw
- CRG from biogas via fermentation
  - Maize and manure
  - Residues

Table 13: Foreground data for land use change for biofuels (own assumptions)

Share of direct land use change (LUC) for biofuels	2019	2030	2050
sugar cane (from pasture)	10%	10%	10%
soja beans (from pasture)	10%	10%	10%
palm oil (from trop. forest)	10%	10%	10%

Table 14: Foreground data for biomass mix for biofuels (EEA 2018, UFOP 2018, ePURE 2018 and own assumptions)

Country		EU28		
		2019	2030	2050
FAME				
	rape seed oil	52%	52%	52%
	used cooking oil	36%	36%	36%
	palm oil	5%	5%	5%
	soja oil	7%	7%	7%
HVO				
	rape seed oil	52%	52%	52%
	used cooking oil	36%	36%	36%
	palm oil	5%	5%	5%
	soja oil	7%	7%	7%
EtOH				
	wheat&maize	68%	64%	53%
	sugar beet	18%	17%	14%
	sugar cane	10%	9%	8%
	wood	2%	5%	13%
	straw	2%	5%	12%
FT-diesel				
	wood	50%	50%	50%
	straw	50%	50%	50%
CRG				
from fermentation				
	maize silage & manure	68%	61%	54%
	residues	32%	29%	26%
from gasification				
	wood	0%	5%	10%
	straw	0%	5%	10%

5.3.4 Electricity Mix

For the different countries the national consumption electricity mix is taken based on IEA statistics for the year 2018 (IEA 2019). The data for 2030 and 2050 are taken form the EU Reference Scenario 2016: Energy, transport and GHG emissions – Trends to 2050" (EU 2018).

The national electricity consumption mix consists on the national electricity generation and the imported electricity. For the European countries it is assumed that the imported electricity is the average additional European electricity generation mix from oil, gas, coal and nuclear. For the considered non-European countries, the imported electricity is not relevant.

If a country exports more electricity than imports electricity, then only the national electricity generation is considered. For countries that import more electricity than export electricity the net-import (as the difference of import and export) is used to calculate the environmental effects.

For the coproduced heat in combined heat and power (CHP) plants an energy allocation to heat and electricity is applied.

Possible differences of the methodological approach and its application on the GHG emissions compared to the GHG emission published in the past by Environmental Agencies and Ministries in AT, DE and CH are described and explained in the Annex II. The main differences identified are due

- Source of data for electricity data
- Considered year
- Generic data for environmental effects of power plants
- Handling of imports and exports
- Assumptions for imported electricity and
- Handling of coproduced heat in CHP plants

For the electric vehicles using only fluctuating renewable electricity from PV and wind, also a storage system is integrated, to reflect possible differences of the timing of the production of the electricity and the charging of the electric vehicle.

- Share of electricity mix (Table 15, Table 16 and Table 17)
    - Coal
    - Oil
    - Gas
    - Nuclear
    - Biomass
    - Wind
    - Hydro

- PV
- Waste
- Other
- Import
- Export and
- Import netto (Import minus export)

The allocation factor of the greenhouse gas emission and primary energy demand to electricity and heat in CHP plants in 2019 (coal, oil, gas and biomass) to electricity are (based on IEA statistics and eurostat)

- AT: 57%
- DE: 82%
- IT: 77%
- PT: 80%
- PL: 75%
- AU: 95%
- CA: 95%

For all other countries no allocation is applied. These allocations were also used or 2030 and 2050

.

Table 15: Foreground data for electricity mixes 2019 (IEA 2019)

2019	Europe 28	Austria	Germany	Switzerland	Italy	United Kingdom	Spain	Portugal	Poland	Australia	Canada
	EU	**AT**	**DE**	**CH**	**IT**	**UK**	**ES**	**PT**	**PL**	**AU**	**CA**
coal	21.0%	5.3%	35.7%	0.0%	11.0%	5.2%	13.9%	19.7%	77.7%	60.3%	8.6%
oil	3.0%	1.0%	0.9%	0.1%	3.7%	0.4%	5.6%	1.9%	0.0%	0.6%	1.2%
natural gas	22.0%	14.8%	12.6%	1.4%	44.1%	39.6%	20.2%	25.1%	7.9%	18.1%	8.8%
nuclear	21.0%	0.0%	11.6%	36.1%	0.0%	18.6%	20.2%	0.0%	0.0%	0.0%	15.0%
biomass	3.0%	7.2%	8.3%	2.4%	6.1%	10.4%	2.6%	5.2%	3.8%	1.5%	2.0%
hydro	10.0%	60.7%	3.6%	55.3%	17.7%	2.4%	13.9%	24.0%	1.5%	7.4%	56.8%
wind	15.0%	8.2%	18.3%	0.2%	6.2%	17.9%	18.8%	21.4%	8.1%	7.1%	6.2%
PV	2.0%	1.8%	7.5%	2.8%	8.2%	4.1%	4.6%	1.9%	0.2%	5.0%	1.3%
waste	3.0%	1.0%	1.1%	1.7%	0.8%	1.4%	0.2%	0.5%	0.8%	0.0%	0.0%
other	0.0%	0.0%	0.3%	0.0%	2.3%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%
SUM	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Import	0.0%	38.0%	5.5%	44.9%	14.6%	6.1%	8.8%	10.2%	8.6%	0.0%	2.2%
Export	0.0%	-25.9%	-14.0%	-48.6%	-1.0%	-0.6%	-4.7%	-14.9%	-5.1%	0.0%	-10.2%
Import Netto	0.0%	12.1%	-8.4%	-3.7%	13.6%	5.4%	4.1%	-4.8%	3.6%	0.0%	-8.0%

Table 16: Foreground data for electricity mixes 2030 (EU 2018)

2030	Europe 28	Austria	Germany	Switzerland	Italy	United Kingdom	Spain	Portugal	Poland	Australia	Canada
	EU	**AT**	**DE**	**CH**	**IT**	**UK**	**ES**	**PT**	**PL**	**AU**	**CA**
coal	16.0%	4.1%	38.0%	0.0%	13.8%	0.9%	5.3%	0.0%	65.0%	45.7%	0.1%
oil	0.6%	0.1%	0.5%	0.1%	2.4%	0.7%	0.6%	2.7%	0.2%	2.4%	0.2%
natural gas	18.6%	18.3%	17.8%	8.5%	37.9%	27.2%	17.4%	10.7%	14.9%	16.8%	11.1%
nuclear	22.1%	0.0%	0.0%	21.1%	0.0%	26.9%	20.0%	0.0%	0.0%	5.0%	11.8%
biomass	8.3%	5.1%	8.9%	1.8%	9.8%	16.6%	3.1%	6.5%	7.8%	4.3%	1.8%
hydro	10.7%	55.7%	3.9%	56.4%	15.4%	1.4%	11.7%	39.1%	1.4%	6.3%	61.5%
wind	17.3%	12.6%	21.0%	1.2%	10.1%	24.0%	25.1%	32.3%	10.7%	14.1%	11.9%
PV	6.6%	4.1%	9.9%	7.7%	10.5%	2.3%	16.9%	8.8%	0.0%	5.5%	1.6%
waste	0.0%	0.0%	0.0%	3.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
other	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SUM	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Import	0.0%	19.3%	4.0%	50.0%	11.1%	4.1%	4.4%	15.0%	4.2%	0.0%	3.0%
Export	0.0%	-15.0%	-1.4%	-40.0%	-1.3%	-0.8%	-2.7%	-4.3%	-3.5%	0.0%	-0.5%
Import Netto	0.0%	4.3%	2.6%	10.0%	9.8%	3.3%	1.7%	10.7%	0.7%	0.0%	2.5%

Table 17: Foreground data for electricity mixes 2050 (EU 2018)

2050	Europe 28	Austria	Germany	Switzerland	Italy	United Kingdom	Spain	Portugal	Poland	Australia	Canada
	EU	**AT**	**DE**	**CH**	**IT**	**UK**	**ES**	**PT**	**PL**	**AU**	**CA**
coal	6.2%	0.0%	21.1%	0.0%	0.0%	0.7%	0.2%	0.0%	25.9%	15.0%	0.1%
oil	0.1%	0.0%	0.1%	0.0%	0.2%	0.1%	0.5%	0.9%	0.1%	2.0%	0.2%
natural gas	20.6%	19.3%	19.3%	23.3%	34.4%	29.6%	13.5%	2.7%	17.0%	10.0%	11.1%
nuclear	18.1%	0.0%	0.0%	0.0%	0.0%	29.1%	0.0%	0.0%	28.2%	15.0%	11.8%
biomass	10.0%	7.6%	11.7%	3.7%	16.6%	11.2%	3.8%	8.1%	8.5%	10.0%	1.8%
hydro	10.4%	50.5%	4.7%	50.0%	12.9%	1.1%	10.6%	36.7%	1.8%	8.0%	61.5%
wind	24.1%	17.0%	30.2%	3.3%	14.9%	26.2%	38.9%	36.9%	18.3%	30.0%	11.9%
PV	10.6%	5.6%	12.8%	18.3%	21.0%	1.9%	32.6%	14.8%	0.1%	10.0%	1.6%
waste	0.0%	0.0%	0.0%	1.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
other	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
SUM	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Import	0.0%	13.4%	3.8%	20.0%	6.9%	1.7%	4.0%	11.4%	4.2%	0.0%	1.0%
Export	0.0%	-10.4%	-1.3%	-10.0%	-0.8%	-0.3%	-5.5%	-3.3%	-3.5%	0.0%	0.0%
Import Netto	0.0%	3.0%	2.5%	10.0%	6.0%	1.4%	-1.5%	8.2%	0.7%	0.0%	1.0%

5.3.5 Possible Future Developments

The foreground data for the possible future development are shown in Table 18, which are only relevant to adjust the background data for 2030 and 2050, as the other foreground data are specified for 2030 and 2050 already explicitly.

- Future development (“decarbonisation”):
    - Carbon capture and storage (CCS)
    - Change in energy efficiency
    - Change in share of renewable energy

The share of carbon capture and storage addresses the fossil fuel power plants, where the CO_2 is collected and stored underground, which reduces the CO_2 emissions from the combustion but additional energy is needed for the separation, compression, transportation and storage of the CO_2, which decreases the net energy efficiency.

The change in energy efficiency describes the degree the overall energy system becomes more efficient in 2030 and 2050 compared to 2019. So all processes for the background data become more energy efficient, which means less GHG emissions and less cumulated primary energy demand.

The change in share of renewable energy means that in 2030 and 2050 more renewable energy is used, so the share of cumulated primary renewable energy is increasing like the share of fossil cumulated energy is decreasing.

The combination of these three indicators calculate the background data for 2030 and 2050, which are used to calculate the GHG emission and the cumulated primary energy demand of the future transportation systems in 2030 and 2050.

For emerging technologies - FT-diesel and CRG from gasification, H_2 and E-fuels – an additional increase in the energy efficiency is possible to be considered.

Table 18: Foreground data for possible future developments

	2019	2030	2050
Carbon capture and storage (CCS)	0%	1%	5%
Change in share of renewable energy	0%	20%	30%
Change in energy efficiency	0%	15%	25%
Additional efficiency for emerging technologies*)	0%	12%	8%
*) FT-diesel and CRG from gasificaion, H2 and E-fuels			

5.4 Background Data

The background data cover all other data that are necessary to estimate the LCA based GHG emissions and the cumulated primary energy demand of the transportation systems with passenger vehicles. These data derive from different data bases (e.g. GEMIS 2017, ecoinvent 2017) and own data. In the following the most relevant background data are shown that are necessary to assess and discuss the main results of the LCA.

The background data are grouped the following

- Vehicle production
- Supply of energy carriers to the vehicle
- Land use change for raw materials for biofuels

5.4.1 Vehicle Production

The background data for vehicle production cover

- Share of material mix for vehicles (Table 19) to calculate the environmental effects from vehicle production
- Materials and energy for vehicle production (Table 20)

Table 19: Background data for material mix of vehicles (without battery, fuel cell and ICE) (based on Hausberger et al. 2019 and JOANNEUM RESEARCH 2019)

Propulsion	ICE	ICE	ICE	PHEV	PHEV	PHEV	BEV	HFC
Fuel	petrol & blending, bio-ethanol	diesel & blending, biodiesel	CNG & blending, CRG	petrol & electricity	diesel & electricity	CNG & electricity	electricity	hydrogen (H2)
steel	55.3%	53.9%	57.1%	54.9%	53.6%	56.2%	49.4%	49.2%
cast iron	8.7%	10.3%	8.6%	10.7%	12.0%	10.6%	5.9%	5.9%
aluminium	11.6%	13.0%	11.5%	10.6%	11.9%	10.4%	17.9%	17.8%
glas	2.6%	2.4%	2.6%	2.3%	2.2%	2.3%	2.7%	2.7%
paint	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
plastic	13.3%	12.0%	11.8%	12.0%	10.9%	11.0%	12.9%	13.3%
rubber	4.3%	4.0%	4.2%	3.9%	3.6%	3.8%	4.4%	4.4%
oil	0.9%	1.0%	0.9%	0.9%	1.0%	0.9%	0.4%	0.4%
copper	2.5%	2.5%	2.5%	3.2%	3.1%	3.1%	4.1%	4.0%
non ferrous metals	0.3%	0.5%	0.3%	1.2%	1.3%	1.2%	1.8%	1.8%
SUM	100%	100%	100%	100%	100%	100%	100%	100%

Table 20: Background data for Materials and energy for vehicle production (JOANNEUM RESEARCH 2019 and GEMIS 2019)

Materials for vehicle production	2019			2030			2050		
	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}
	[gCO_2eq/kg]	[kWh/kg]	[kWh/kg]	[gCO_2eq/kg]	[kWh/kg]	[kWh/kg]	[gCO_2eq/kg]	[kWh/kg]	[kWh/kg]
aluminium	12,100	53	45	9,100	48	42	7,630	45	39
cast iron	905	3.5	3.1	690	3.2	2.8	580	3	2.6
copper	3,610	12	11	2,750	11	9.8	2,320	10	9.2
galvanized steel	2,470	8.9	7.6	1,890	8.1	7	1,600	7.5	6.5
not iron metals	7,670	30	23	5,810	28	22	4,880	26	21
lithium	11,400	195	140	8,520	180	130	7,100	165	120
nickel	2,990	44	26	2,290	40	25	1,940	37	24
platin	27,400	78	76	21,000	71	69	17,800	66	65
propylene	3,610	8.6	7.3	2,710	7.8	6.7	2,260	7.3	6.4
carbon fiber	1,560	20	16	1,210	18	15	1,030	17	14
rubber	3,300	9.9	9.3	2,490	9	8.5	2,080	8.4	8

5.4.2 Supply of Energy Carriers to Vehicle

The background data for the supply of energy carriers to the vehicle are:

- Heating values of fossil and biogenic resources (Table 21)
- Heating values of fuels (Table 22)
- Supply of fossil fuels to the filling station (Table 23)
- Supply of biofuels to the filling station (Table 24)
- Supply of electricity to the charging station (Table 25)

- Supply of hydrogen to the filling station (Table 26)
- Supply of E-fuels to the filling station (Table 27)

These background data were calculated with the specified foreground data using LCA (JOANNEUM RESEARCH 2019). Further details on the background data are shown in chapter 10.2 to 10.4.

Table 21: Background data for heating values of fossil and biogenic resources (JOANNEUM RESEARCH 2019)

Fossil resources	**[kWh/kg]**	**[kWh/Nm³]**
hard coal	7.6	
lignite	2.8	
raw oil	11.1	
natural gas		10.0
Biomass resources	**[kWh/kg]**	
wood	3.7	
maize	2.8	
wheat	3.9	
sugar beet	0.8	
rape seeds	6.8	
soy beans	4.7	
palm oil fruits	6.2	
sugar cane	2.5	
maize sillage	1.5	
straw	3.9	
used cooking oil	10.3	
bio-waste (DM)	2.2	
manure (DM)	3.0	

Table 22: Background data for heating values of fuels (JOANNEUM RESEARCH 2019 comparable to EU 2018a)

	[kWh/kg]	[kWh/l]	[kWh/Nm³]
diesel	11.8	9.8	
petrol	11.9	8.8	
CNG	15.4		10.0
diesel B7		9.7	
petrol E5		8.7	
petrol E10		8.5	
FAME	10.3	9.1	
HVO	12.2	9.5	
FT-diesel	12.2	10.2	
EtOH	7.4	5.8	
CRG	15.4		10.0
H2	33.3		
E-fuel FT-diesel	12.2	10.2	
E-fuel CRG	15.4		10.0

Table 23: Background data for the supply of fossil fuels to the filling station (JOANNEUM RESEARCH 2019)

Fuel supply	2019			2030			2050		
	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}
	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]
diesel / raw oil	45	1.2	1.2	37	1.2	1.2	34	1.2	1.2
diesel / raw oil - oil sands	175	1.6	1.6	145	1.6	1.6	130	1.6	1.6
petrol / raw oil	69	1.3	1.3	58	1.3	1.3	52	1.3	1.3
petrol / raw oil - oil sands	200	1.7	1.7	165	1.7	1.7	150	1.7	1.7
CNG / natural gas	38	1.1	1.1	33	1.1	1.1	31	1.1	1.1
CNG / natural gas - fracking	130	1.4	1.4	115	1.3	1.3	105	1.3	1.3

Table 24: Background data for the supply of biofuels to the filling station (JOANNEUM RESEARCH 2019)

Supply of biofuels	2019			2030			2050		
	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}
	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]
EtOH / wheat&maize	255	2.5	0.91	220	2.5	0.88	200	2.5	0.87
EtOH / sugar beet	265	2.3	1.00	225	2.3	1.00	205	2.3	1.00
EtOH / sugar cane	99	5.1	0.25	78	4.5	0.23	66	4.1	0.21
EtOH / wood	41	2.1	0.12	34	2.1	0.10	31	2.2	0.09
EtOH / straw	77	2.0	0.17	70	2.1	0.15	66	2.1	0.15
FAME / rape seed oil	205	2.2	0.46	190	2.2	0.46	185	2.2	0.45
FAME / waste cooking oil	16	1.1	0.13	14	1.1	0.12	12	1.1	0.12
FAME / palm oil	220	4.7	0.56	185	4.2	0.51	160	3.8	0.48
FAME / soja oil	52	1.9	0.36	38	1.8	0.34	31	1.8	0.33
HVO / rape seed oil	240	2.4	0.57	210	2.4	0.54	200	2.4	0.53
HVO / waste cooking oil	49	1.3	0.23	33	1.2	0.21	26	1.2	0.20
HVO / palm oil	255	4.9	0.66	200	4.3	0.60	175	4.0	0.56
HVO / soja oil	85	2.1	0.46	58	2.0	0.43	45	1.9	0.41
CRG / maize silage & manure	67	2.0	0.62	43	1.9	0.61	30	1.9	0.59
CRG / residues	54	1.7	0.24	44	1.7	0.23	39	1.7	0.22
CRG / wood	5	1.5	0.01	3.7	1.3	0.06	3.1	1.3	0.08
CRG / straw	34	1.5	0.06	30	1.4	0.10	27	1.3	0.12
FT-diesel / straw	69	1.9	0.17	59	1.8	0.21	54	1.7	0.23
FT-diesel / wood	34	1.9	0.11	29	1.7	0.16	26	1.6	0.18

Table 25: Background data for the supply of electricity to the charging station (JOANNEUM RESEARCH 2019 based on electricity mix defined in foreground data)[5]

Supply of electricity to the charging station	2019			2030			2050		
	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}
	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]
electr. / hydro	7	1.1	0.02	6.7	1.1	0.02	6.7	1.1	0.02
electr. / wind	11	1.1	0.03	11	1.1	0.03	11	1.1	0.03
electr. / PV	60	1.3	0.21	59	1.3	0.21	59	1.3	0.20
electr. / EU28	425	2.6	2.20	305	2.3	1.70	200	2.1	1.30
electr. / AT	160	1.5	0.70	110	1.3	0.44	80	1.2	0.35
electr. / DE	415	2.2	1.70	435	1.9	1.30	285	1.7	0.89
electr. / CH	55	2.2	1.40	140	2.0	1.30	175	1.6	0.82
electr. / IT	370	2.0	1.50	325	1.8	1.20	180	1.6	0.78
electr. / UK	335	2.6	2.00	210	2.5	1.70	200	2.4	1.80
electr. / ES	350	2.4	1.90	190	2.0	1.40	105	1.4	0.40
electr. / PT	315	1.7	1.10	125	1.5	0.58	67	1.4	0.34
electr. / PL	680	2.2	2.00	590	1.9	1.60	295	2.2	1.80
electr. / AU	735	2.5	2.20	585	2.2	1.80	240	2.0	1.20
electr. / CA	165	1.8	1.10	87	1.6	0.74	74	1.5	0.68

[5] For the electricity mix possible differences of the methodological approach and its application on the GHG emissions compared to GHG emission published in the past by Environmental Agencies and Ministries in AT DE and CH are described and explained in the Annex II.

Table 26: Background data for the supply of hydrogen to the filling station (JOANNEUM RESEARCH 2019)

Supply of hydrogen	2019			2030			2050		
	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}
	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]
H2 / natural gas	385	1.9	1.90	305	1.8	1.70	265	1.7	1.60
H2 / natural gas - fracking	500	2.2	2.10	400	2.0	1.90	350	1.8	1.80
H2 / hydro	13	2.0	0.03	10	1.8	0.00	8.8	1.7	0.00
H2 / wind	22	2.0	0.06	17	1.9	0.03	15	1.8	0.02
H2 / PV	110	2.4	0.39	85	2.2	0.33	72	2.1	0.30

Table 27: Background data for the supply of E-fuels to the filling station (JOANNEUM RESEARCH 2019)

Supply of E-fuels	2019			2030			2050		
	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}	GHG	PED	PED_{foss}
	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]	[gCO_2eq/kWh]	[kWh/kWh]	[kWh/kWh]
E-fuel FT-diesel / wind & CO2 ind.	39	2.5	0.1	30	2.3	0.1	25	2.3	0.081
E-fuel FT-diesel / wind & CO2 air	300	3.8	1.4	180	3.2	0.93	125	2.9	0.7
E-fuel FT-diesel / wind & biomass	25	2.1	0.1	20	1.8	0.033	17	1.7	0.016
E-fuel CRG / wind & CO2 ind.	33	2.2	0.1	26	2.1	0.082	22	2.1	0.066
E-fuel CRG / wind & CO2 air	205	3.1	0.9	125	2.7	0.63	88	2.5	0.47
E-fuel CRG / wind & biomass	22	1.9	0.1	21	2	0.038	20	2.1	0.029
E-fuel FT-diesel / eu_mix & CO2 ind.	990	5.9	5.0	770	5.4	4.5	645	5	4.1
E-fuel FT-diesel / eu_mix & CO2 air	1.250	7.3	6.2	915	6.3	5.3	740	5.7	4.8
E-fuel FT-diesel / eu_mix & biomass	425	3.6	2.1	395	3.7	2.2	360	3.8	2.3
E-fuel CRG / eu_mix & CO2 ind.	895	5.4	4.5	705	4.9	4.1	595	4.6	3.8
E-fuel CRG / eu_mix & CO2 air	1.070	6.3	5.3	800	5.5	4.6	660	5.1	4.2
E-fuel CRG / eu_mix & biomass	390	3.2	1.9	365	3.5	2.1	345	3.6	2.2

5.4.3 Land Use Change for Raw Materials for Biofuels

The background data for land use change for biomass resources are shown in Table 28. The iLUC data are just for illustration and not included in the analysis (see also chapter 3.4.2).

Table 28: Background data for direct and indirect land use change (LUC) for biomass resources (based on EU 2009, EU 2015)

iLUC*)	[gCO_2/MJ]	[gCO_2/kWh]
bioethanol (wheat, maize)	12	43
bioethanol (sugar beet)	13	47
bioetahnol (sugar cane)	17	61
FAME/HVO (rape seeds)	33	119
FAME/HVO (soja beans)	55	198
FAME/HVO (palm oil)	66	238
dLUC*)	[$kgCO_2$/ha]	
sugar cane (greenland)	2.576	
soja beans(greenland)	2.825	
palm oil (trop. forest)	28.441	
	[gCO_2/kWh]	
EtOH / sugar cane	68	
FAME / palm oil	804	
FAME / soja oil	330	
HVO / palm oil	805	
HVO / soja oil	331	
**) in brackets is the previouse use of the land*		

6. Results

In this chapter the results of the LCA based estimation of the GHG emissions and the cumulated primary energy consumption are presented.

6.1 Introduction

The detailed results of each single transportation system are shown in the Fact Sheets (concept see figure 9). The focus here in the report is on the comparison of the different transportation systems for GHG emissions and total primary energy demand only, where of specific interest, e.g. E-fuels and hydrogen. The discussion of the results is done by using 3 groups of possible GHG emissions:

1. "high GHG emission" above 150 g CO_2-eq/km
2. "average GHG emissions" between 70 g CO_2-eq/km and 150 g CO_2-eq/km
3. "low GHG emissions" below 70 g CO_2-eq/km

In a first step the possible ranges of GHG emissions per kilometer of the following 6 groups are presented and discussed

1. Fossil Fuel Internal Combustion Engine Vehicle (ICEV) (incl. biofuel blending)
2. Plug In Hybrid Vehicle (PHEV)
3. Battery Electric Vehicle (BEV)
4. Hydrogen Fuel Cell Vehicle (HFCV)
5. Biofuel Internal Combustion Engine Vehicle (ICEV)
6. E-fuel Internal Combustion Engine Vehicle (ICEV)

In a second step a comparison of selected system for EU 28 from these 6 groups is made based on the cumulated GHG emissions over the life time.

The comparison is made on the "estimated ranges" of GHG emissions and cumulated primary energy demand for each state of technology (2019, 2030 and 2050). The possible development by comparing the different states of technologies is graphically shown based on the "estimated average" GHG emissions and cumulated primary energy demand over time 2019, 2030 and 2050.

6.2 Fossil Fuel Internal Combustion Engine Vehicle (ICEV) (incl. biofuel blending)

In Table 29 the estimated ranges of GHG emissions and primary energy demand for fossil fuel ICEV (incl. biofuel blending) are shown. All of these systems using fossil energy have GHG emissions with current technology higher than 150 g CO_2-eq/km. In future diesel and CNG have GHG emissions below 150 g CO_2-eq/km. The fossil and total cumulated primary energy demand is about the same, as mainly fossil energy is used. Petrol has the highest primary energy demand and natural gas in future the lowest primary energy demand.

In Figure 24 the estimated average GHG emissions for fossil fuel ICEV with current technology are shown. In Figure 25 the possible development of estimated average GHG emissions for fossil fuel ICEV for future technologies is shown, which shows an improvement due to the expected lower fuel consumption of the vehicles.

Table 29: Estimated ranges of GHG emissions and primary energy demand for fossil fuel Internal Combustion Engine Vehicle (ICEV) (incl. biofuel blending)

COMPARISON		GHG [gCO_2eq/km]	PED [kWh/km]	PED_{foss} [kWh/km]
ICE_petrol,raw oil,EU28	2019	230 to 240	0.84 to 0.94	0.82 to 0.92
	2030	200 to 210	0.77 to 0.87	0.75 to 0.85
	2050	165 to 175	0.66 to 0.76	0.64 to 0.74
ICE_petrol E5,raw oil,EU28	2019	225 to 235	0.87 to 0.97	0.81 to 0.91
	2030	195 to 205	0.80 to 0.90	0.74 to 0.84
	2050	160 to 170	0.67 to 0.77	0.63 to 0.73
ICE_petrol E10,raw oil,EU28	2019	225 to 235	0.90 to 1	0.81 to 0.91
	2030	195 to 205	0.82 to 0.92	0.73 to 0.83
	2050	160 to 170	0.69 to 0.79	0.62 to 0.72
ICE_diesel,raw oil,EU28	2019	185 to 195	0.67 to 0.77	0.65 to 0.75
	2030	165 to 175	0.62 to 0.72	0.60 to 0.70
	2050	135 to 145	0.52 to 0.62	0.51 to 0.61
ICE_diesel B7,raw oil,EU28	2019	180 to 190	0.69 to 0.79	0.63 to 0.73
	2030	160 to 170	0.64 to 0.74	0.58 to 0.68
	2050	130 to 140	0.54 to 0.64	0.49 to 0.59
ICE_CNG,natural gas,EU28	2019	175 to 185	0.78 to 0.88	0.77 to 0.87
	2030	155 to 165	0.70 to 0.80	0.68 to 0.78
	2050	125 to 135	0.46 to 0.56	0.45 to 0.55
ICE_CNG CRG5,natural gas,EU28	2019	165 to 175	0.80 to 0.90	0.75 to 0.85
	2030	145 to 155	0.72 to 0.82	0.66 to 0.76
	2050	120 to 130	0.48 to 0.58	0.44 to 0.54

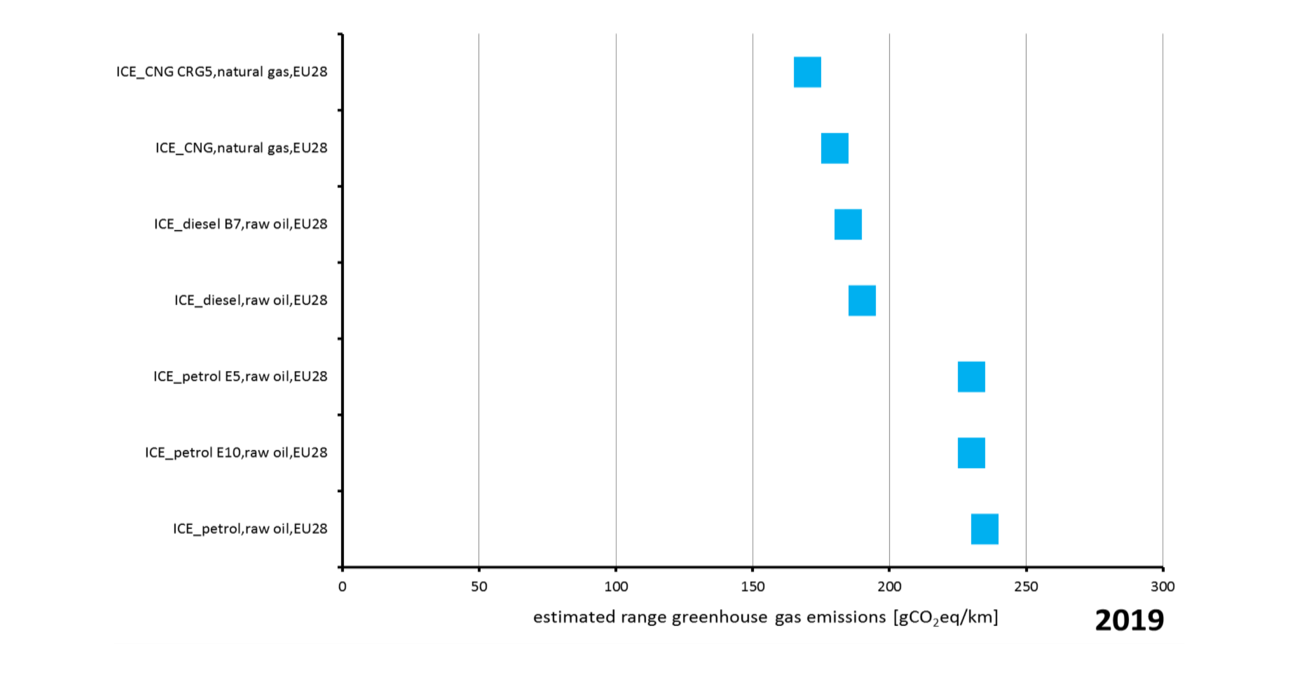


Figure 24: *Estimated ranges of GHG emissions for fossil fuel Internal Combustion Engine Vehicle (ICEV) (incl. biofuel blending) in 2019*

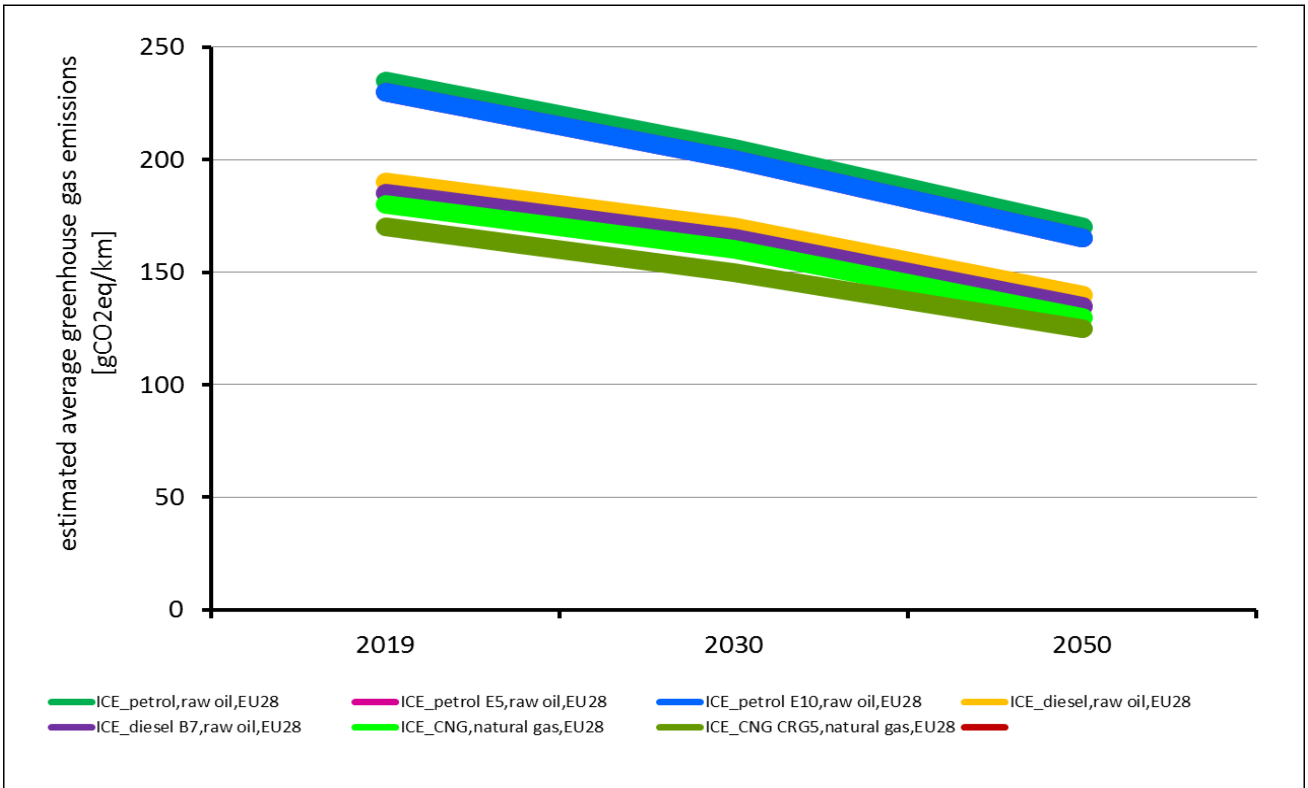


Figure 25: *Possible development of estimated average GHG emissions for fossil fuel Internal Combustion Engine Vehicle (ICEV) (incl. biofuel blending)*

6.3 Plug In Hybrid Vehicle (PHEV)

In Table 30 the estimated ranges of GHG emissions and primary energy for petrol and in Table 31 for diesel PHEV with the electricity mix for the considered countries are shown.

With current technology the GHG emission of PHEV with petrol are higher than 150 g CO_2-eq/km, except for countries that have already a high share of renewable electricity like AT, CH and CA. In future all systems have GHG emission below 150 g CO_2-eq/km due to the expected increasing fuel efficiency and a higher share of renewable electricity, except for countries with still a high share of fossil based electricity mix in 2030. But none of the PHEVS reaches a GHG emission below 70 g CO_2-eq/km.

With current technology the GHG emissions of PHEV with diesel are higher than 150 g CO_2-eq/km, except for countries that have already a high share of renewable electricity like AT, CH and CA. In future all systems have GHG emissions below 150 g CO_2-eq/km due to the increasing fuel efficiency and a higher share of renewable electricity, except for countries with still a high share of fossil based electricity mix in 2030. But none of them is below 70 g CO_2-eq/km.

In Figure 26 the estimated average GHG emissions for petrol and in Figure 27 for diesel PHEV with the electricity mix for the considered countries are shown.

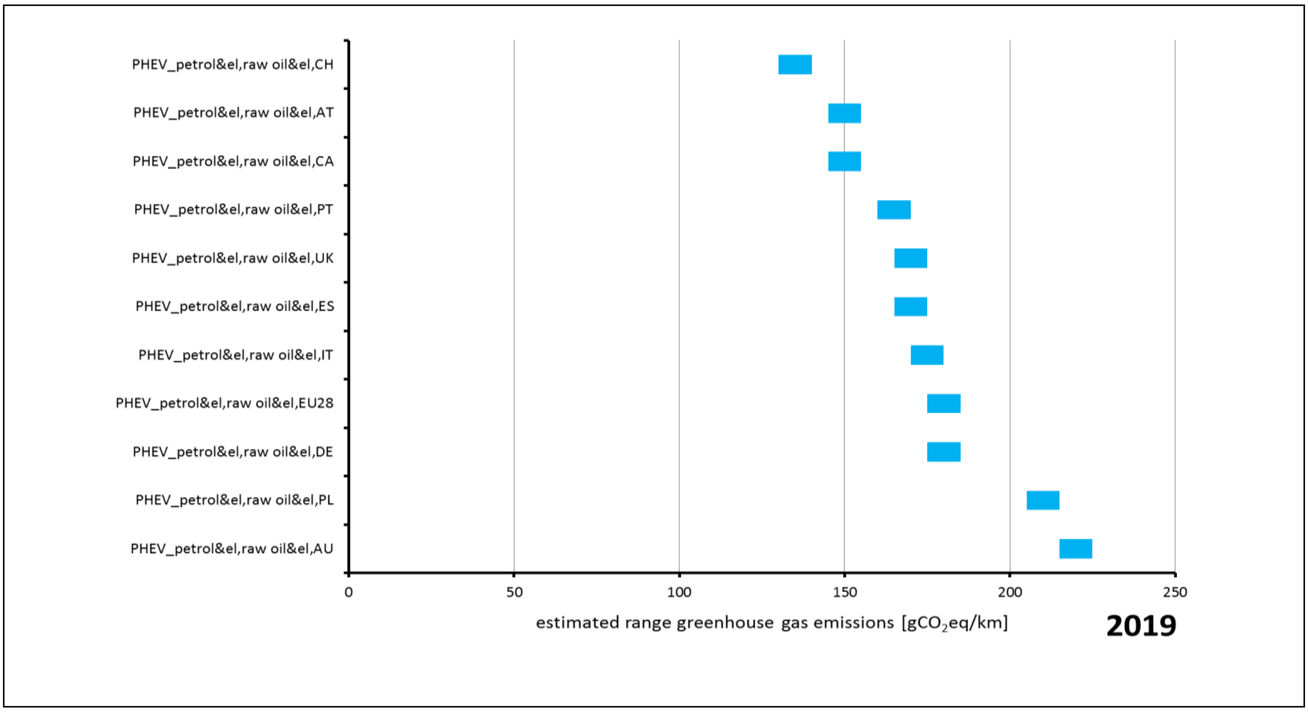
In Figure 28 the possible development of estimated average GHG emissions for petrol and in Figure 29 for diesel PHEV with the electricity mix for the considered countries are shown.

Table 30: Estimated ranges of GHG emissions and primary energy demand for petrol and electricity Plug In Hybrid Vehicle (PHEV)

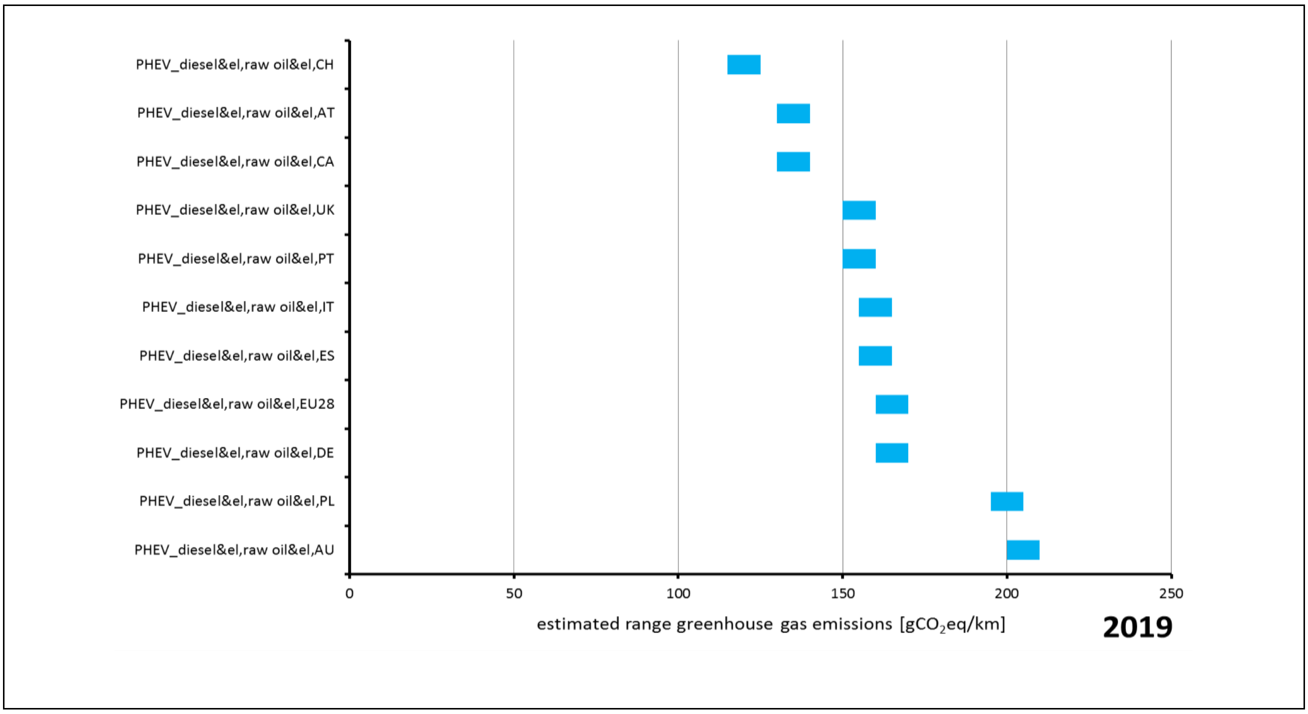
COMPARISON		GHG [gCO_2eq/km]	PED [kWh/km]	PED_{foss} [kWh/km]
PHEV_petrol&el,raw oil&el,EU28	2019	175 to 185	0.76 to 0.86	0.68 to 0.78
	2030	135 to 145	0.65 to 0.75	0.56 to 0.66
	2050	100 to 110	0.5 to 0.60	0.42 to 0.52
PHEV_petrol&el,raw oil&el,AT	2019	145 to 155	0.62 to 0.72	0.5 to 0.60
	2030	115 to 125	0.53 to 0.63	0.42 to 0.52
	2050	88 to 98	0.42 to 0.52	0.33 to 0.43
PHEV_petrol&el,raw oil&el,DE	2019	175 to 185	0.71 to 0.81	0.62 to 0.72
	2030	150 to 160	0.59 to 0.69	0.51 to 0.61
	2050	105 to 115	0.46 to 0.56	0.38 to 0.48
PHEV_petrol&el,raw oil&el,CH	2019	130 to 140	0.70 to 0.80	0.59 to 0.69
	2030	120 to 130	0.61 to 0.71	0.51 to 0.61
	2050	95 to 105	0.46 to 0.56	0.37 to 0.47
PHEV_petrol&el,raw oil&el,IT	2019	170 to 180	0.68 to 0.78	0.61 to 0.71
	2030	140 to 150	0.59 to 0.69	0.5 to 0.60
	2050	95 to 105	0.46 to 0.56	0.37 to 0.47
PHEV_petrol&el,raw oil&el,UK	2019	165 to 175	0.75 to 0.85	0.66 to 0.76
	2030	125 to 135	0.66 to 0.76	0.56 to 0.66
	2050	100 to 110	0.53 to 0.63	0.46 to 0.56
PHEV_petrol&el,raw oil&el,ES	2019	165 to 175	0.73 to 0.83	0.65 to 0.75
	2030	125 to 135	0.61 to 0.71	0.52 to 0.62
	2050	90 to 100	0.44 to 0.54	0.33 to 0.43
PHEV_petrol&el,raw oil&el,PT	2019	160 to 170	0.65 to 0.75	0.55 to 0.65
	2030	115 to 125	0.55 to 0.65	0.43 to 0.53
	2050	87 to 97	0.44 to 0.54	0.33 to 0.43
PHEV_petrol&el,raw oil&el,PL	2019	205 to 215	0.71 to 0.81	0.66 to 0.76
	2030	170 to 180	0.60 to 0.70	0.55 to 0.65
	2050	105 to 115	0.52 to 0.62	0.46 to 0.56
PHEV_petrol&el,raw oil&el,AU	2019	215 to 225	0.74 to 0.84	0.69 to 0.79
	2030	170 to 180	0.63 to 0.73	0.57 to 0.67
	2050	100 to 110	0.49 to 0.59	0.41 to 0.51
PHEV_petrol&el,raw oil&el,CA	2019	145 to 155	0.66 to 0.76	0.55 to 0.65
	2030	110 to 120	0.56 to 0.66	0.45 to 0.55
	2050	87 to 97	0.45 to 0.55	0.36 to 0.46

<u>Table 31:</u> Estimated ranges of GHG emissions and primary energy demand for diesel and electricity Plug In Hybrid Vehicle (PHEV)

COMPARISON		GHG [gCO_2eq/km]	PED [kWh/km]	PED_{foss} [kWh/km]
PHEV_diesel&el,raw oil&el,EU28	2019	160 to 170	0.71 to 0.81	0.63 to 0.73
	2030	125 to 135	0.60 to 0.70	0.51 to 0.61
	2050	89 to 99	0.46 to 0.56	0.37 to 0.47
PHEV_diesel&el,raw oil&el,AT	2019	130 to 140	0.57 to 0.67	0.45 to 0.55
	2030	105 to 115	0.48 to 0.58	0.37 to 0.47
	2050	78 to 88	0.38 to 0.48	0.29 to 0.39
PHEV_diesel&el,raw oil&el,DE	2019	160 to 170	0.66 to 0.76	0.57 to 0.67
	2030	140 to 150	0.55 to 0.65	0.46 to 0.56
	2050	95 to 105	0.42 to 0.52	0.34 to 0.44
PHEV_diesel&el,raw oil&el,CH	2019	115 to 125	0.65 to 0.75	0.54 to 0.64
	2030	105 to 115	0.56 to 0.66	0.46 to 0.56
	2050	87 to 97	0.42 to 0.52	0.33 to 0.43
PHEV_diesel&el,raw oil&el,IT	2019	155 to 165	0.63 to 0.73	0.55 to 0.65
	2030	125 to 135	0.54 to 0.64	0.46 to 0.56
	2050	87 to 97	0.42 to 0.52	0.33 to 0.43
PHEV_diesel&el,raw oil&el,UK	2019	150 to 160	0.70 to 0.80	0.61 to 0.71
	2030	115 to 125	0.62 to 0.72	0.51 to 0.61
	2050	89 to 99	0.49 to 0.59	0.41 to 0.51
PHEV_diesel&el,raw oil&el,ES	2019	155 to 165	0.68 to 0.78	0.60 to 0.70
	2030	115 to 125	0.57 to 0.67	0.47 to 0.57
	2050	80 to 90	0.40 to 0.5	0.29 to 0.39
PHEV_diesel&el,raw oil&el,PT	2019	150 to 160	0.60 to 0.70	0.5 to 0.60
	2030	105 to 115	0.5 to 0.60	0.38 to 0.48
	2050	77 to 87	0.40 to 0.5	0.29 to 0.39
PHEV_diesel&el,raw oil&el,PL	2019	195 to 205	0.66 to 0.76	0.61 to 0.71
	2030	155 to 165	0.55 to 0.65	0.5 to 0.60
	2050	100 to 110	0.47 to 0.57	0.42 to 0.52
PHEV_diesel&el,raw oil&el,AU	2019	200 to 210	0.69 to 0.79	0.64 to 0.74
	2030	155 to 165	0.59 to 0.69	0.52 to 0.62
	2050	93 to 105	0.45 to 0.55	0.36 to 0.46
PHEV_diesel&el,raw oil&el,CA	2019	130 to 140	0.61 to 0.71	0.5 to 0.60
	2030	100 to 110	0.51 to 0.61	0.40 to 0.5
	2050	78 to 88	0.41 to 0.51	0.32 to 0.42



<u>Figure 26:</u> Estimated ranges of GHG emissions for petrol and electricity Plug In Hybrid Vehicle (PHEV)



<u>Figure 27:</u> Estimated ranges of GHG emissions for diesel and electricity Plug In Hybrid Vehicle (PHEV)

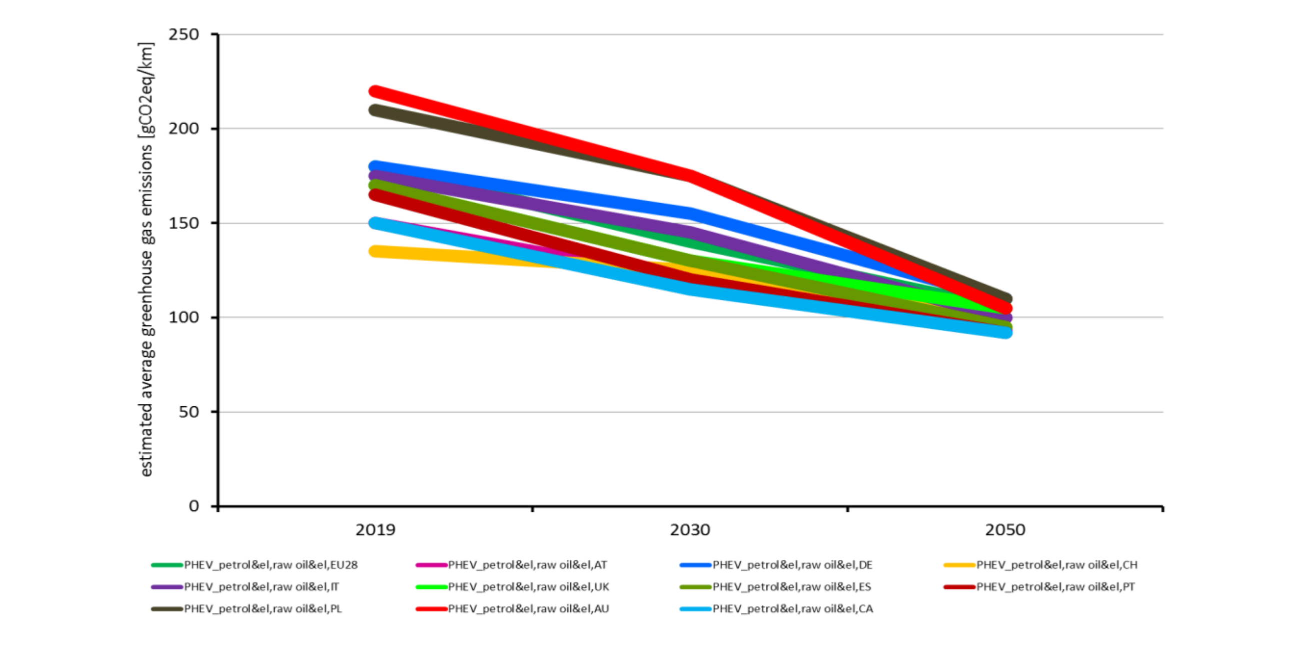


Figure 28: Possible development of estimated average GHG emissions for petrol and electricity Plug In Hybrid Vehicle (PHEV)

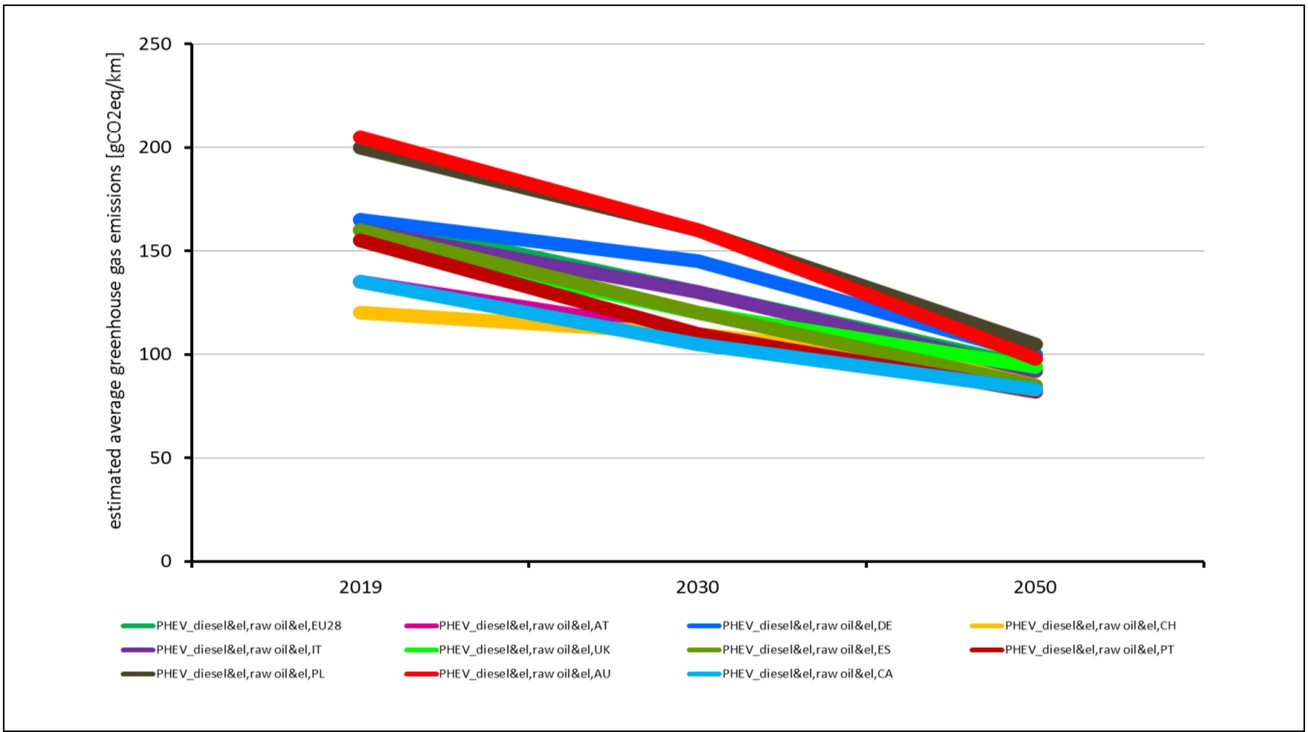


Figure 29: Possible development of estimated average GHG emissions for diesel and electricity Plug In Hybrid Vehicle (PHEV)

6.4 Battery Electric Vehicle (BEV)

In Table 32 the estimated ranges of GHG emissions and primary energy for Battery Electric Vehicle (BEV) for the considered countries and in Table 33 for renewable electricity are shown.

With current technology the GHG emissions of BEV are all lower than 150 g CO_2-eq/km, except for countries that still have a high share of fossil based electricity like PL and AU. In the future all systems have GHG emissions below 150 g CO_2-eq/km due to the increasing energy efficiency of the vehicle and a higher share of renewable electricity. In countries with a very high share of renewable electricity like AT, CH, CA the GHG emissions are still below 100 g CO_2-eq/km. With renewable electricity the GHG emissions are already with current technologies very low (below 70 g CO_2-eq/km).

In Figure 30 the estimated average GHG emissions for BEV for the considered countries and in Figure 31 for renewable electricity in EU 28 are shown. In Figure 32 the possible development of estimated average GHG emissions BEV for the considered countries and in Figure 33 for renewable electricity in EU 28 are shown. In future BEV using renewable electricity have GHG emissions below 30 g CO_2-eq/km.

Table 32: Estimated ranges of GHG emissions and primary energy demand for Battery Electric vehicles (BEV) for the considered countries

COMPARISON		GHG [gCO_2eq/km]	PED [kWh/km]	PED_{foss} [kWh/km]
BEV_electr.,mix,EU28	2019	140 to 150	0.75 to 0.85	0.62 to 0.72
	2030	91 to 100	0.60 to 0.70	0.45 to 0.55
	2050	49 to 59	0.44 to 0.54	0.28 to 0.38
BEV_electr.,mix,AT	2019	83 to 93	0.51 to 0.61	0.31 to 0.41
	2030	53 to 63	0.39 to 0.49	0.20 to 0.30
	2050	28 to 38	0.29 to 0.39	0.12 to 0.22
BEV_electr.,mix,DE	2019	135 to 145	0.67 to 0.77	0.52 to 0.62
	2030	115 to 125	0.51 to 0.61	0.37 to 0.47
	2050	63 to 73	0.37 to 0.47	0.21 to 0.31
BEV_electr.,mix,CH	2019	60 to 70	0.66 to 0.76	0.46 to 0.56
	2030	58 to 68	0.54 to 0.64	0.36 to 0.46
	2050	44 to 54	0.36 to 0.46	0.20 to 0.30
BEV_electr.,mix,IT	2019	125 to 135	0.62 to 0.72	0.49 to 0.59
	2030	95 to 105	0.5 to 0.60	0.36 to 0.46
	2050	45 to 55	0.36 to 0.46	0.19 to 0.29
BEV_electr.,mix,UK	2019	120 to 130	0.74 to 0.84	0.58 to 0.68
	2030	72 to 82	0.63 to 0.73	0.45 to 0.55
	2050	48 to 58	0.5 to 0.60	0.36 to 0.46
BEV_electr.,mix,ES	2019	125 to 135	0.70 to 0.80	0.57 to 0.67
	2030	69 to 79	0.54 to 0.64	0.38 to 0.48
	2050	32 to 42	0.32 to 0.42	0.13 to 0.23
BEV_electr.,mix,PT	2019	115 to 125	0.56 to 0.66	0.39 to 0.49
	2030	56 to 66	0.43 to 0.53	0.23 to 0.33
	2050	26 to 36	0.32 to 0.42	0.12 to 0.22
BEV_electr.,mix,PL	2019	195 to 205	0.66 to 0.76	0.59 to 0.69
	2030	150 to 160	0.52 to 0.62	0.43 to 0.53
	2050	65 to 75	0.47 to 0.57	0.37 to 0.47
BEV_electr.,mix,AU	2019	205 to 215	0.72 to 0.82	0.63 to 0.73
	2030	145 to 155	0.58 to 0.68	0.47 to 0.57
	2050	55 to 65	0.43 to 0.53	0.27 to 0.37
BEV_electr.,mix,CA	2019	83 to 93	0.58 to 0.68	0.39 to 0.49
	2030	48 to 58	0.45 to 0.55	0.26 to 0.36
	2050	27 to 37	0.35 to 0.45	0.18 to 0.28

Table 33: Estimated ranges of GHG emissions and primary energy demand for Battery Electric vehicles (BEV) for renewable electricity

COMPARISON		GHG [gCO_2eq/km]	PED [kWh/km]	PED_{foss} [kWh/km]
BEV_electr.,hydro,EU28	2019	50 to 60	0.42 to 0.52	0.17 to 0.27
	2030	32 to 42	0.35 to 0.45	0.12 to 0.22
	2050	15 to 25	0.27 to 0.37	0.060 to 0.16
BEV_electr.,wind,EU28	2019	51 to 61	0.43 to 0.53	0.17 to 0.27
	2030	33 to 43	0.36 to 0.46	0.12 to 0.22
	2050	16 to 26	0.27 to 0.37	0.060 to 0.16
BEV_electr.,PV,EU28	2019	62 to 72	0.5 to 0.60	0.21 to 0.31
	2030	44 to 54	0.43 to 0.53	0.16 to 0.26
	2050	25 to 35	0.33 to 0.43	0.10 to 0.20

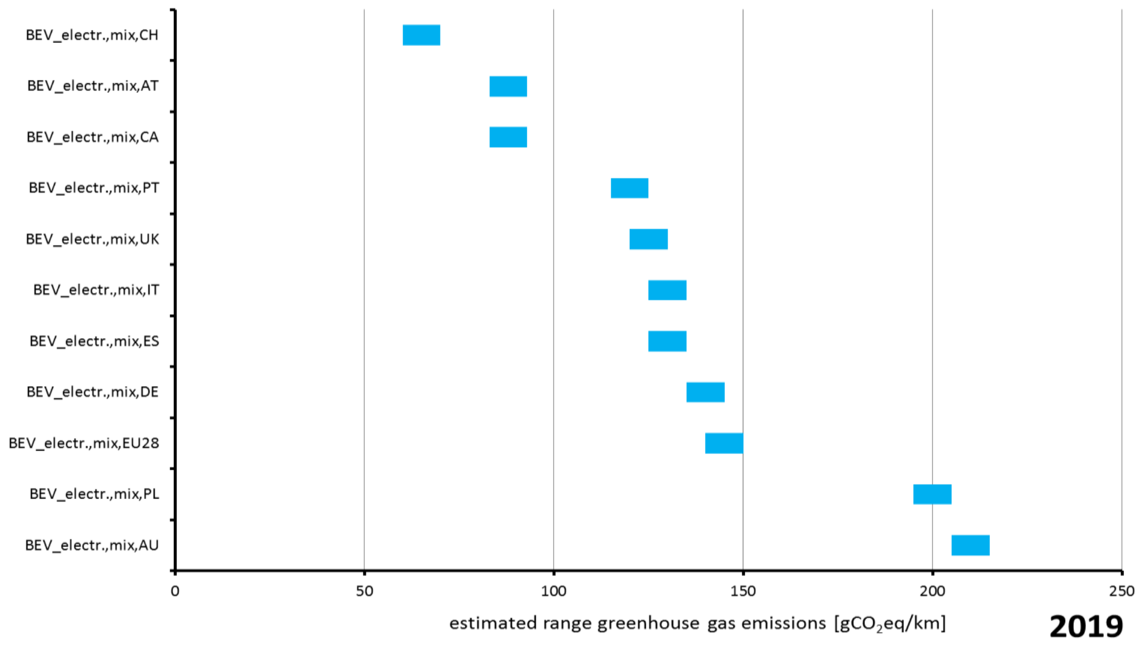


Figure 30: Estimated ranges of GHG emissions for Battery Electric vehicles (BEV) for the considered countries

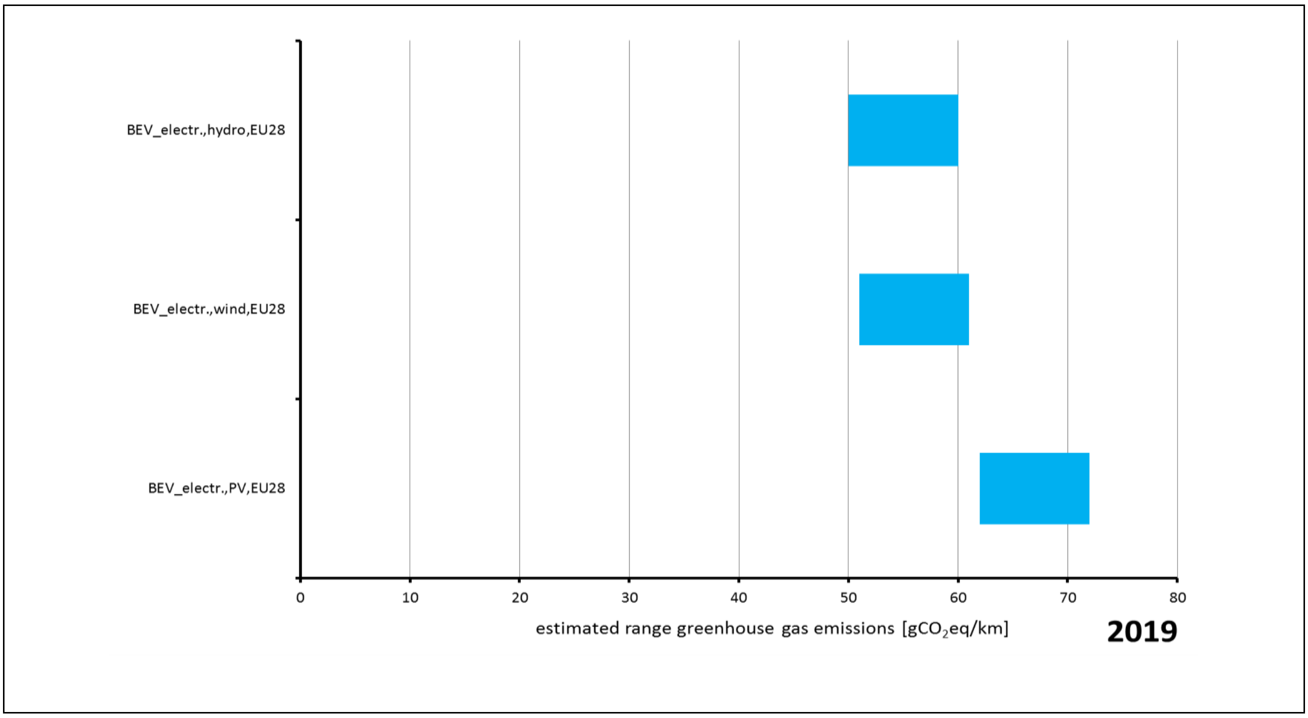


Figure 31: *Estimated ranges of GHG emissions for Battery Electric vehicles (BEV) for renewable electricity*

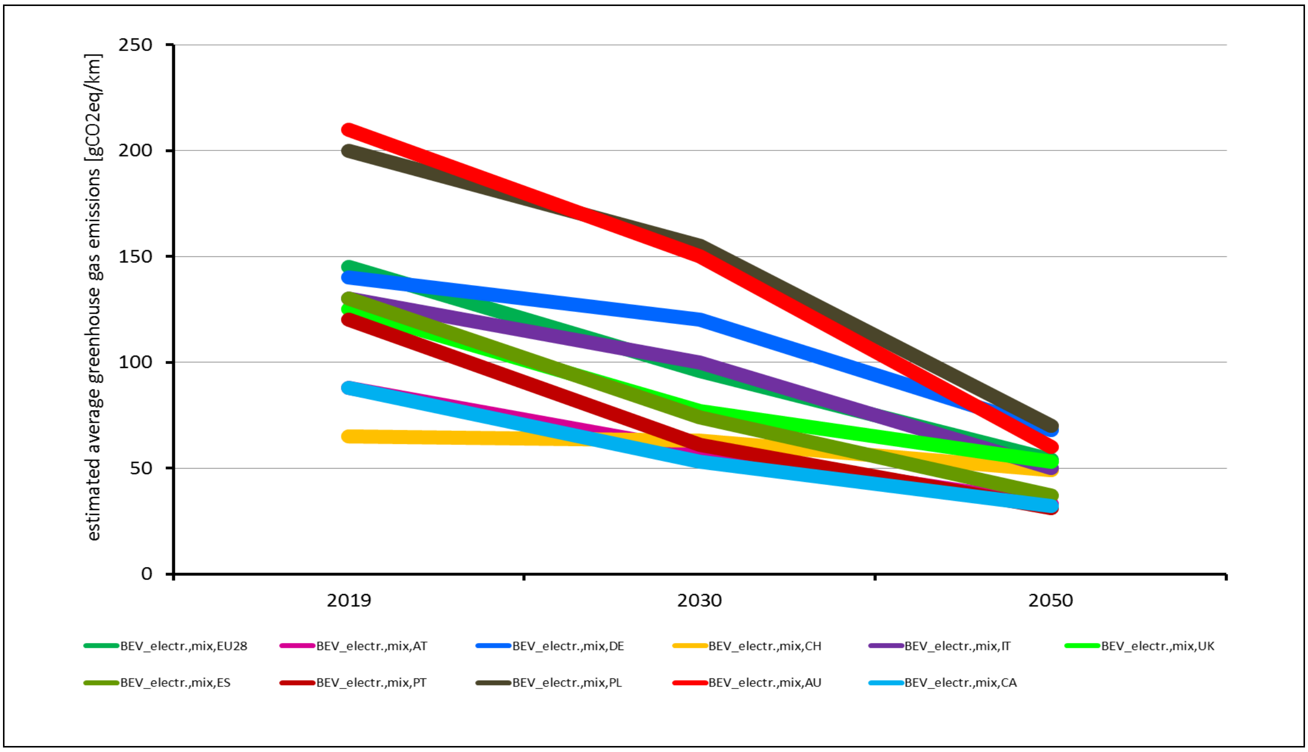


Figure 32: *Possible development of estimated average GHG emissions for Battery Electric vehicles (BEV) for the considered countries*

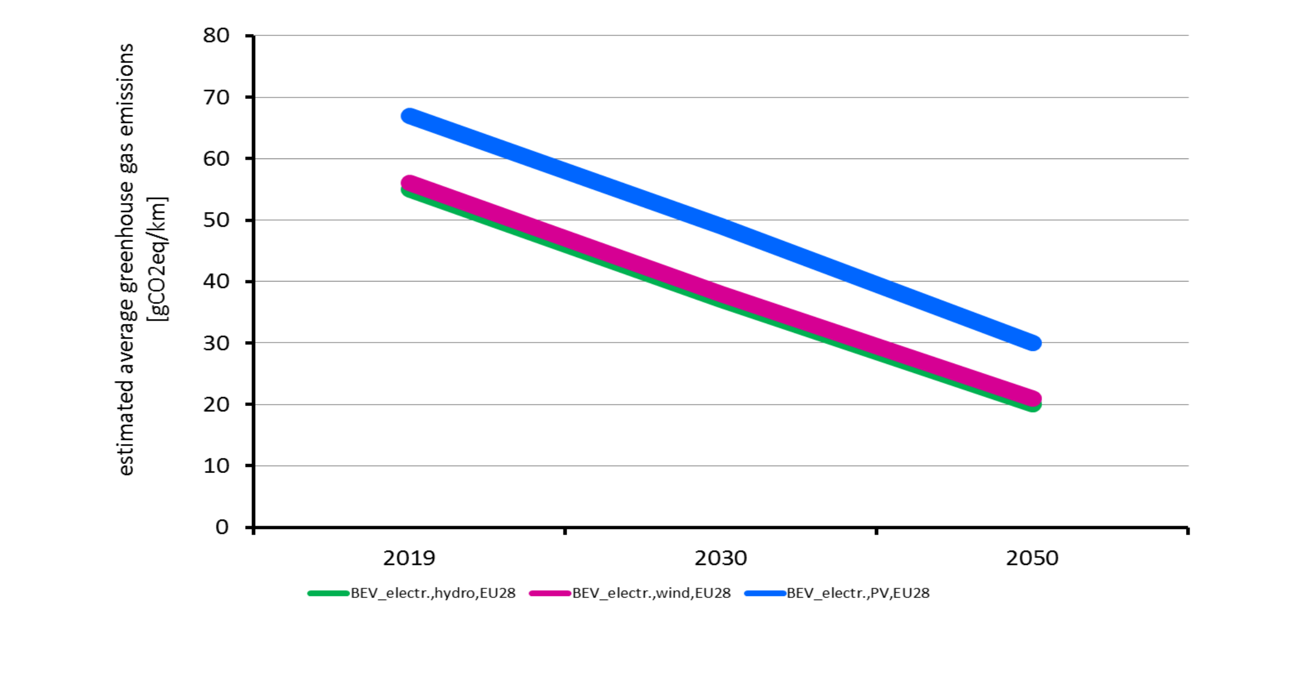


Figure 33: Possible development of estimated average GHG emissions for Battery Electric vehicles (BEV) for renewable electricity

6.5 Hydrogen Fuel Cell Vehicle (HFCV)

In Table 34 the estimated ranges of GHG emissions and primary energy for HFCV are shown. The estimated average GHG emissions for HFCV in 2019 are shown in Figure 34.

With current technology using natural gas for hydrogen the GHG emissions of HFCV are above 150 g CO_2-eq/km. With future technologies all the HFCV have GHG emissions below 150 g CO_2-eq/km. Hydrogen from renewable electricity (except PV with current technology) have GHG emission below 70 g CO_2-eq/km. In future the HFCV have GHG emission below 30 g CO_2-eq/km if hydrogen is made from electricity of wind and hydro power.

The estimated average primary energy demand for HFCV in 2019 shows that hydrogen from PV has a higher primary energy consumption than from hydro and wind power. The cumulated primary energy demand of hydrogen from natural gas is lower than hydrogen from hydro power, wind power and PV. The estimated average fossil primary energy demand for HFCV in 2019 shows that hydrogen from natural gas has the highest and from hydro power the lowest primary energy consumption. The fossil primary energy consumption from wind is similar to hydrogen from hydro power. Hydrogen from PV has higher fossil primary energy consumption than from hydro power but significantly lower than from natural gas.

In Figure 35 the possible development of estimated average GHG emissions for HFCV are shown, which are expected to decrease significantly due to improvements in the energy efficiency.

Table 34: Estimated ranges of GHG emissions and primary energy demand for Hydrogen Fuel Cell Vehicle (HFCV)

COMPARISON		**GHG** [gCO_2eq/km]	**PED** [kWh/km]	**PED_{foss}** [kWh/km]
HFC_H2,natural gas,EU28	2019	170 to 180	0.81 to 0.91	0.76 to 0.86
	2030	120 to 130	0.64 to 0.74	0.59 to 0.69
	2050	84 to 94	0.41 to 0.51	0.37 to 0.47
HFC_H2,hydro,EU28	2019	46 to 56	0.83 to 0.93	0.14 to 0.24
	2030	28 to 38	0.68 to 0.78	0.090 to 0.19
	2050	15 to 25	0.52 to 0.62	0.040 to 0.14
HFC_H2,wind,EU28	2019	49 to 59	0.85 to 0.95	0.15 to 0.25
	2030	31 to 41	0.69 to 0.79	0.090 to 0.19
	2050	17 to 27	0.53 to 0.63	0.046 to 0.15
HFC_H2,PV,EU28	2019	80 to 90	0.97 to 1.1	0.26 to 0.36
	2030	52 to 62	0.79 to 0.89	0.19 to 0.29
	2050	32 to 42	0.61 to 0.71	0.12 to 0.22

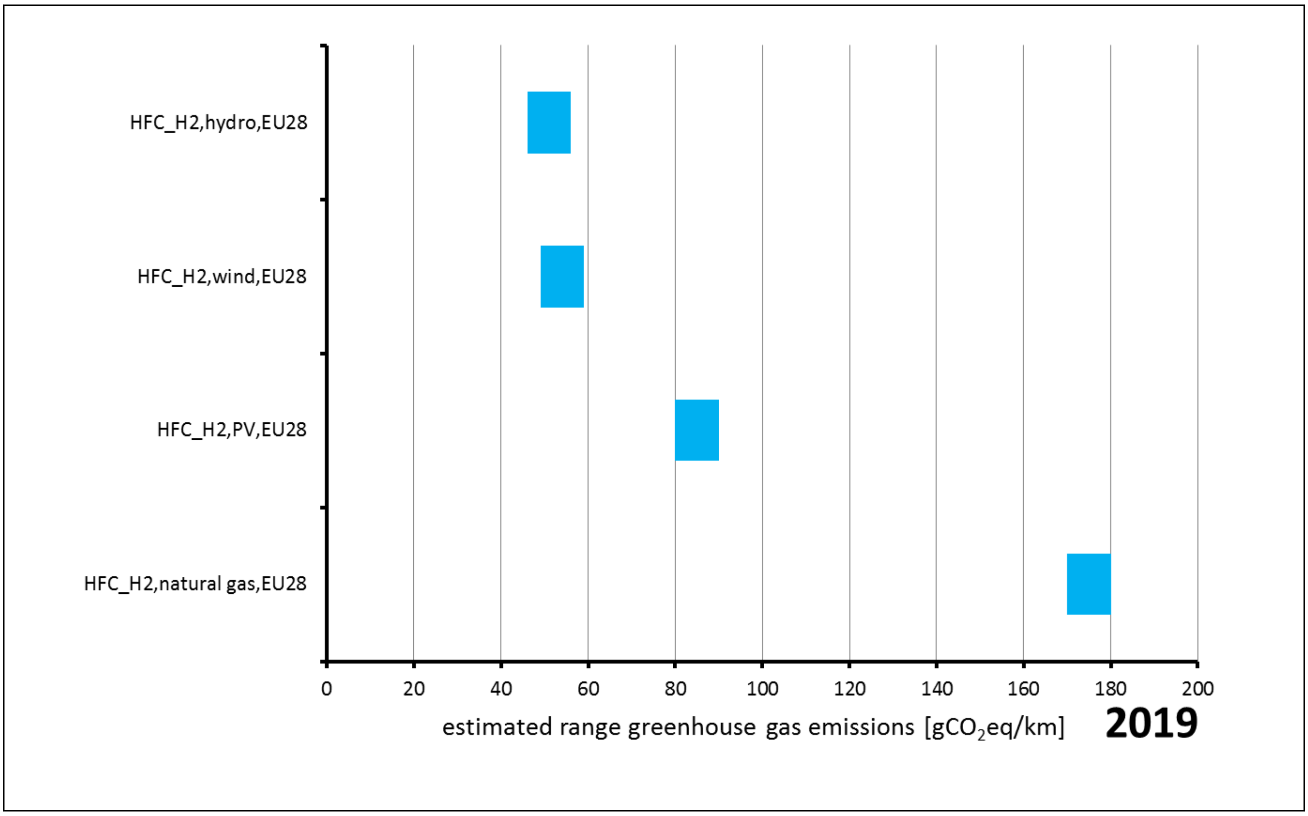


Figure 34: *Estimated ranges of GHG emissions for Hydrogen Fuel Cell Vehicle (HFCV) in 2019*

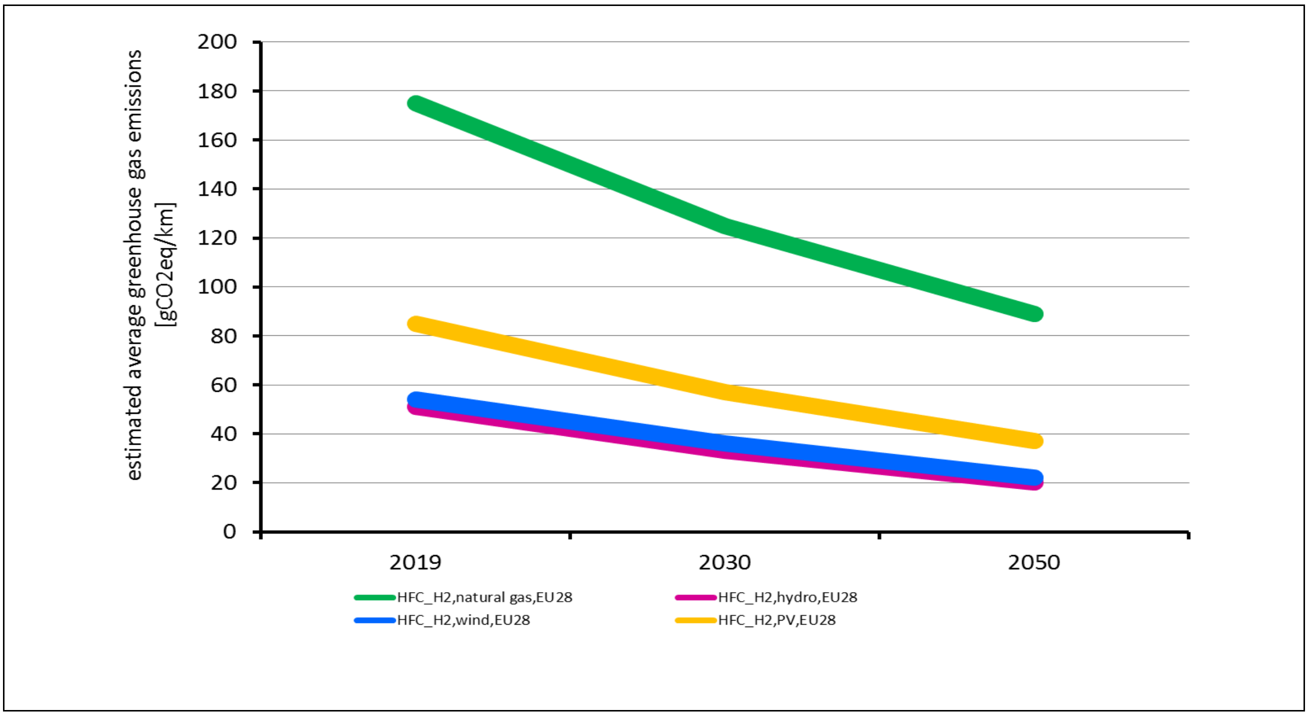


Figure 35: *Possible development of estimated average GHG emissions for Hydrogen Fuel Cell Vehicle (HFCV)*

6.6 Biofuel Internal Combustion Engine Vehicle (ICEV)

In Table 35 the estimated ranges of GHG emissions and primary energy for biofuel ICEV are shown, where all biofuels use a mix of different types of biomass resources (see chapter 5.3.3). The estimated average GHG emissions for biofuel ICEV in 2019 are shown in Figure 36.

Only bioethanol with current technology using agricultural crops as raw material and fossil energy for processing has GHG emissions above 150 g CO_2-eq/km. All other biofuels have GHG emissions between 70 g CO_2-eq/km and 150 g CO_2-eq/km, except FT-diesel and CRG have GHG emissions of current technology below 70 g CO_2-eq/km.

The estimated average primary energy demand for biofuel ICEV in 2019 shows that EtOH has the highest primary energy consumption, the cumulated primary energy consumption of all other biofuels is almost in the same range.

The estimated average fossil primary energy demand for biofuel ICEV in 2019 shows that EtOH has the highest fossil primary energy consumption, due to the use of fossil fuels for process heat and FT-diesel has the lowest fossil primary energy demand.

In Figure 37 the possible development of estimated average GHG emissions for ICEV are shown. Due to the change of biogenic raw material towards wood and straw and the increasing energy efficiency of the ICE the GHG emissions are expected to decrease significantly.

Table 35: Estimated ranges of GHG emissions and primary energy demand for Biofuel Internal Combustion Engine Vehicle (ICEV)

COMPARISON		GHG [gCO_2eq/km]	PED [kWh/km]	PED_{foss} [kWh/km]
ICE_FAME,mix,EU28	2019	110 to 120	1.1 to 1.2	0.23 to 0.33
	2030	92 to 100	0.95 to 1.1	0.21 to 0.31
	2050	71 to 81	0.76 to 0.86	0.15 to 0.25
ICE_HVO,mix,EU28	2019	125 to 135	1.2 to 1.3	0.29 to 0.39
	2030	100 to 110	1 to 1.1	0.25 to 0.35
	2050	76 to 86	0.82 to 0.92	0.18 to 0.28
ICE_EtOH,mix,EU28	2019	170 to 180	1.8 to 1.9	0.56 to 0.66
	2030	125 to 135	1.5 to 1.6	0.47 to 0.57
	2050	78 to 88	1.2 to 1.3	0.30 to 0.40
ICE_FT-diesel,mix,EU28	2019	52 to 62	1.1 to 1.2	0.13 to 0.23
	2030	40 to 50	0.89 to 0.99	0.14 to 0.24
	2050	27 to 37	0.68 to 0.78	0.10 to 0.20
ICE_CRG,mix,EU28	2019	62 to 72	1.2 to 1.3	0.36 to 0.46
	2030	38 to 48	1 to 1.1	0.29 to 0.39
	2050	19 to 29	0.72 to 0.82	0.19 to 0.29

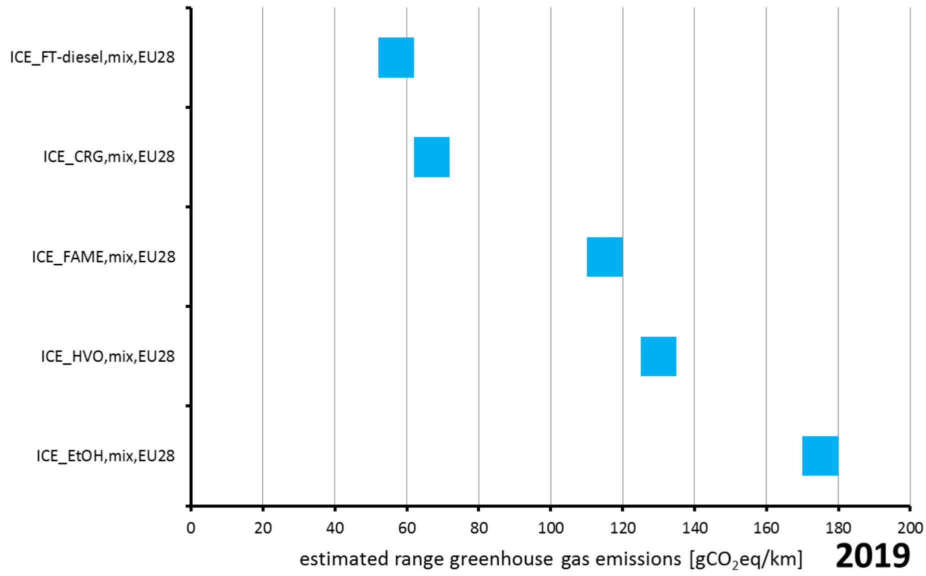


Figure 36: Estimated ranges of GHG emissions for Biofuel Internal Combustion Engine Vehicle (ICEV) in 2019

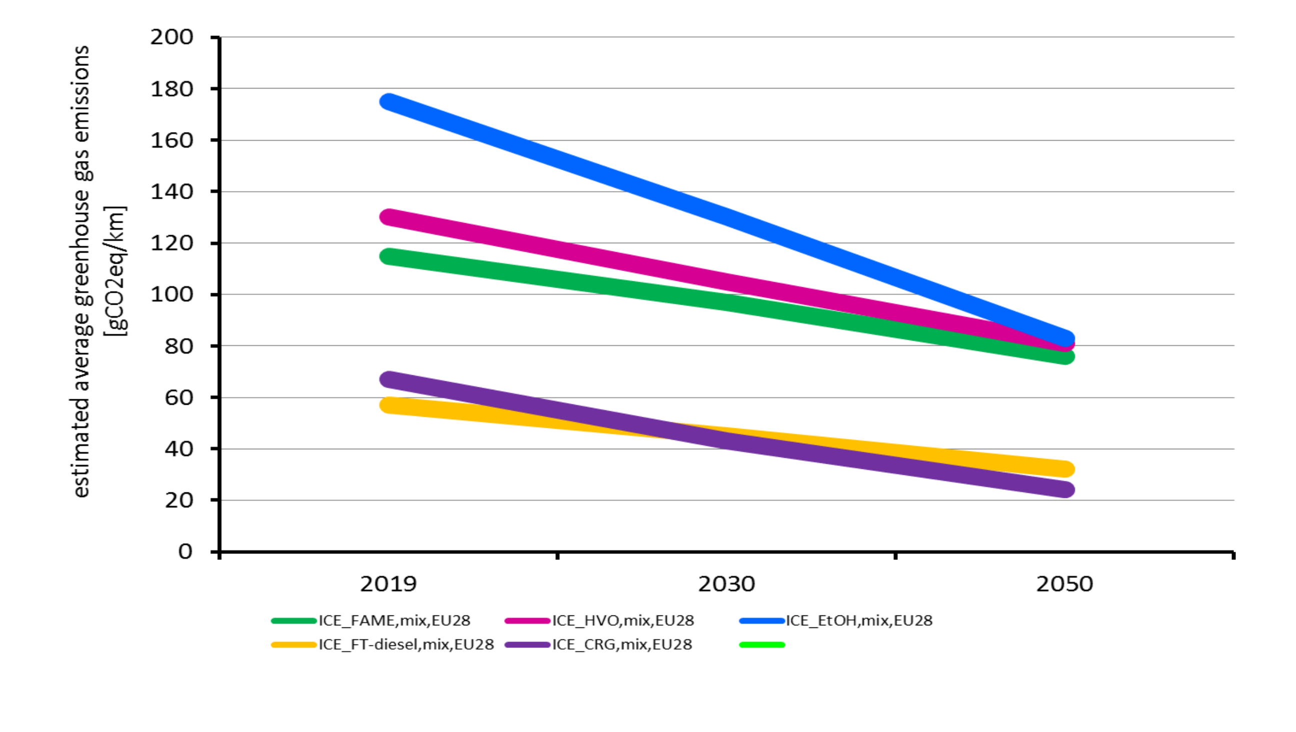


Figure 37: Possible development of estimated average GHG emissions for Biofuel Internal Combustion Engine Vehicle (ICEV)

6.7 E-fuel Internal Combustion Engine Vehicle (ICEV)

In Table 36 the estimated ranges of GHG emissions and primary energy for FT-diesel and in Table 37 for CRG as E-fuel ICEV are shown. The estimated average GHG emissions for E-fuel ICEV for FT-diesel are shown in Figure 38 and for CRG in Figure 39.

With current technology using the EU 28 electricity mix the GHG emissions are significantly higher than 150 g CO_2-eq/km, even petrol and diesel have lower GHG emissions. If renewable electricity is used for the E-fuel the GHG emissions are below 70 g CO_2-eq/km, except if CO_2 from the atmosphere with current technology is used. As the CO_2 concentration in an industrial flue gas with 10 – 15 vol.-% is higher than in air (400 ppm = 0.04%) less energy is needed for CO_2 separation, which is directly connected to the energy demand of the E-fuels. The primary energy demand of E-fuel that use biomass as CO_2 source is higher due to the low energy density of biomass and conversion efficiency of biomass to FT-diesel and CRG (see also biofuels in chapter 6.6). The differences between FT diesel and CRG are small and not significant.

The possible development of estimated average GHG emissions for E-fuel for Internal Combustion Engine Vehicle (ICEV) is shown in Figure 40 for FT-diesel and in Figure 41 for CRG. A significant decreasing of GHG emissions using EU28 electricity mix is expected due to the strongly increasing share of renewable electricity in future Europe. If already renewable electricity is used only a smaller GHG reduction is expected mainly due to the increasing energy efficiency of the ICE.

Table 36: Estimated ranges of GHG emissions and primary energy demand for FT diesel as E-fuel for Internal Combustion Engine Vehicle (ICEV)

COMPARISON		GHG [gCO_2eq/km]	PED [kWh/km]	PED_{foss} [kWh/km]
ICE_E-fuel FT-diesel,wind&CO2ind,EU28	2019	46 to 56	1.36 to 1.46	0.13 to 0.23
	2030	33 to 43	1.17 to 1.27	0.1 to 0.2
	2050	20 to 30	0.92 to 1.02	0.05 to 0.15
ICE_E-fuel FT-diesel,wind&CO2air,EU28	2019	180 to 190	2.07 to 2.17	0.78 to 0.88
	2030	95 to 105	1.59 to 1.69	0.47 to 0.57
	2050	53 to 63	1.17 to 1.27	0.26 to 0.36
ICE_E-fuel FT-diesel,wind&biomass,EU28	2019	52 to 62	2.3 to 2.4	0.13 to 0.23
	2030	41 to 51	2.12 to 2.22	0.1 to 0.2
	2050	27 to 37	1.75 to 1.85	0.06 to 0.16
ICE_E-fuel FT-diesel,eumix&CO2ind,EU28	2019	540 to 550	3.16 to 3.26	2.64 to 2.74
	2030	285 to 295	2.46 to 2.56	1.83 to 1.93
	2050	140 to 150	1.75 to 1.85	1.11 to 1.21
ICE_E-fuel FT-diesel,eumix&CO2air,EU28	2019	675 to 685	3.86 to 3.96	3.29 to 3.39
	2030	350 to 360	2.88 to 2.98	2.2 to 2.3
	2050	170 to 180	2 to 2.1	1.33 to 1.43
ICE_E-fuel FT-diesel,eumix&biomass,EU28	2019	515 to 525	3.98 to 4.08	2.47 to 2.57
	2030	280 to 290	3.27 to 3.37	1.74 to 1.84
	2050	140 to 150	2.45 to 2.55	1.07 to 1.17

Table 37: Estimated ranges of GHG emissions and primary energy demand for CRG as E-fuel for Internal Combustion Engine Vehicle (ICEV)

COMPARISON		GHG [gCO_2eq/km]	PED [kWh/km]	PED_{foss} [kWh/km]
ICE_E-fuel CRG,wind&CO2ind,EU28	2019	43 to 53	1.46 to 1.56	0.12 to 0.22
	2030	31 to 41	1.28 to 1.38	0.09 to 0.19
	2050	19 to 29	1 to 1.1	0.045 to 0.15
ICE_E-fuel CRG,wind&CO2air,EU28	2019	150 to 160	2.02 to 2.12	0.64 to 0.74
	2030	82 to 92	1.61 to 1.71	0.38 to 0.48
	2050	45 to 55	1.21 to 1.31	0.21 to 0.31
ICE_E-fuel CRG,wind&biomass,EU28	2019	51 to 61	2.55 to 2.65	0.12 to 0.22
	2030	40 to 50	2.27 to 2.37	0.1 to 0.2
	2050	26 to 36	1.82 to 1.92	0.06 to 0.16
ICE_E-fuel CRG,eumix&CO2ind,EU28	2019	585 to 595	3.43 to 3.53	2.87 to 2.97
	2030	310 to 320	2.7 to 2.8	2.02 to 2.12
	2050	150 to 160	1.93 to 2.03	1.23 to 1.33
ICE_E-fuel CRG,eumix&CO2air,EU28	2019	695 to 705	3.99 to 4.09	3.39 to 3.49
	2030	365 to 375	3.03 to 3.13	2.31 to 2.41
	2050	175 to 185	2.13 to 2.23	1.4 to 1.5
ICE_E-fuel CRG,eumix&biomass,EU28	2019	610 to 620	4.58 to 4.68	2.96 to 3.06
	2030	330 to 340	3.73 to 3.83	2.08 to 2.18
	2050	160 to 170	2.77 to 2.87	1.27 to 1.37

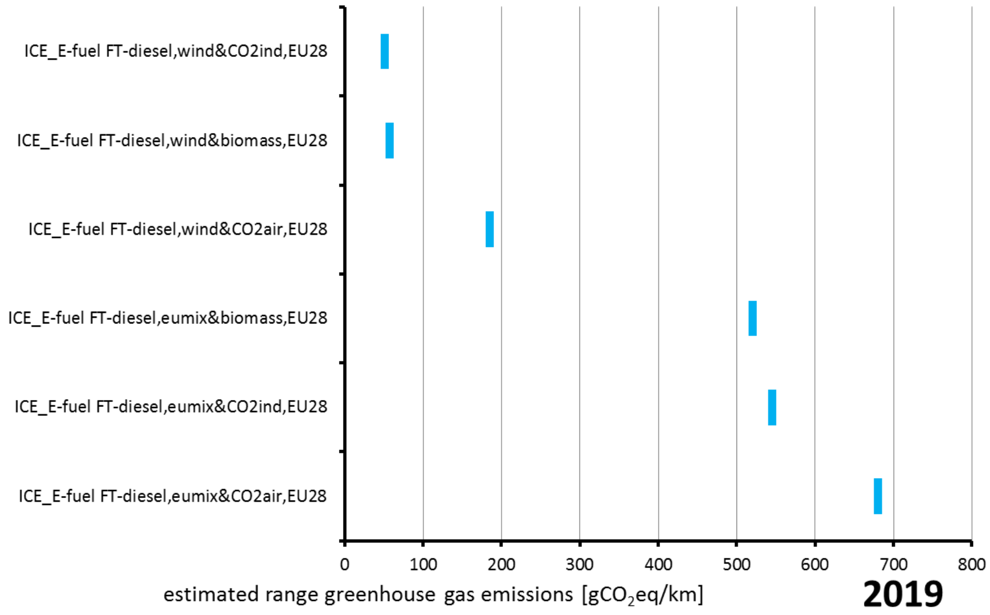


Figure 38: Estimated ranges of GHG emissions for FT-diesel as E-fuel for Internal Combustion Engine Vehicle (ICEV) in 2019

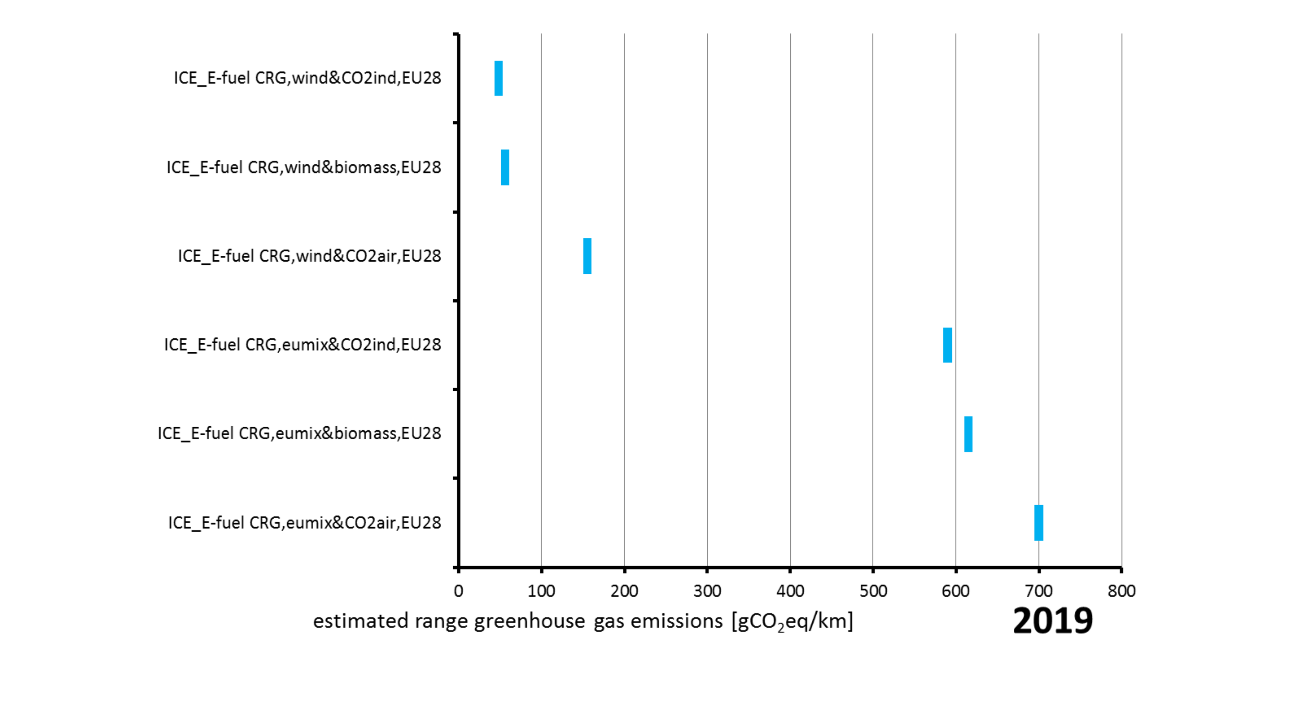


Figure 39: *Estimated ranges of GHG emissions for CRG as E-fuel for Internal Combustion Engine Vehicle (ICEV) in 2019*

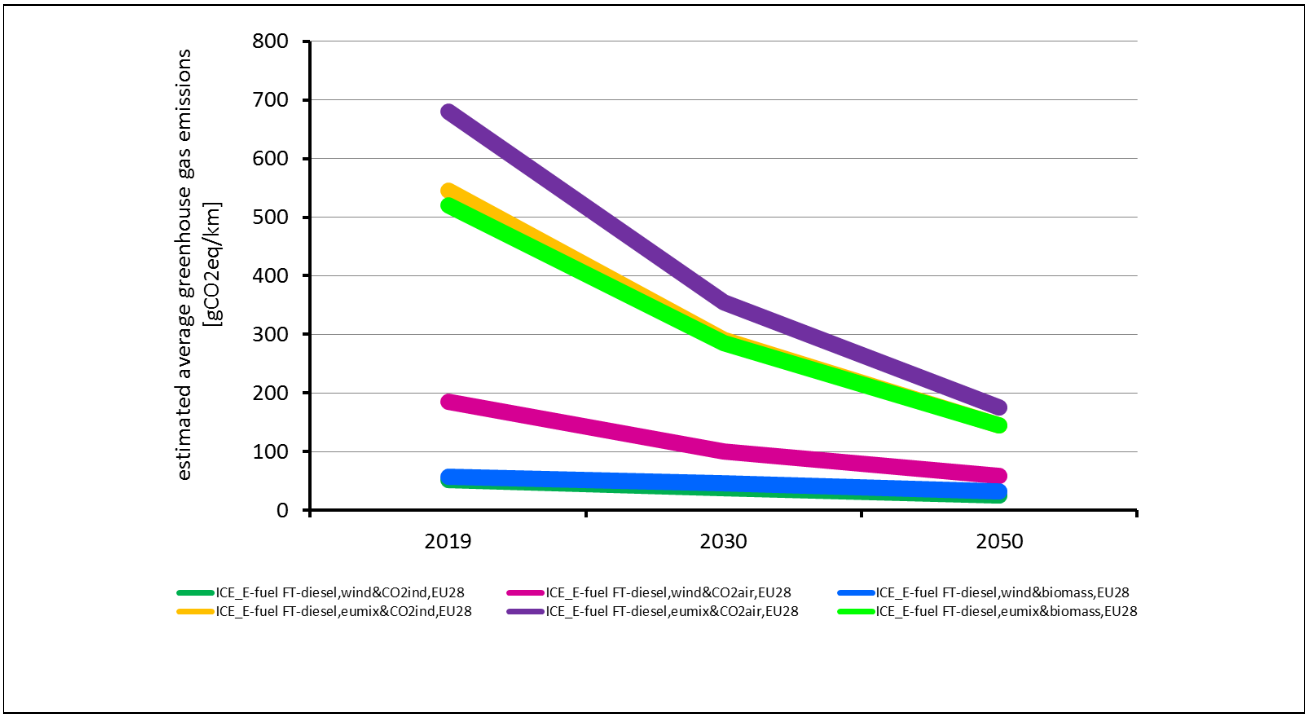


Figure 40: *Possible development of estimated average GHG emissions for FT-diesel as E-fuel for Internal Combustion Engine Vehicle (ICEV)*

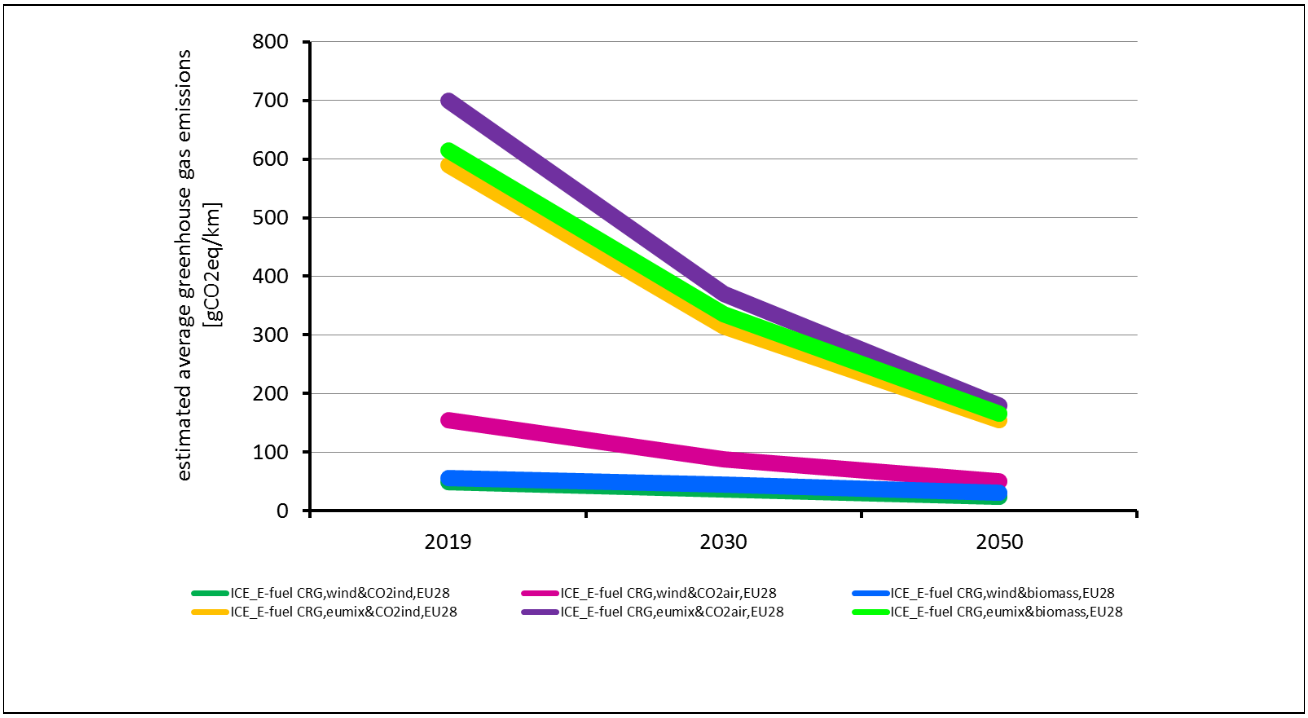


Figure 41: Possible development of estimated average GHG emissions for CRG as E-fuel for Internal Combustion Engine Vehicle (ICEV)

6.8 System Comparison for EU28

In this chapter selected transportation systems for EU 28 are compared to show and identify the main differences between the systems results presented in the previous chapters. The selection always includes a comparison between the following 6 transportation systems:

1. Fossil Fuel Internal Combustion Engine Vehicle (ICEV) (incl. biofuel blending)
2. Plug In Hybrid Vehicle (PHEV)
3. Battery Electric Vehicle (BEV)
4. Hydrogen Fuel Cell Vehicle (HFCV)
5. Biofuel Internal Combustion Engine Vehicle (ICEV)
6. E-fuel Internal Combustion Engine Vehicle (ICEV)

6.8.1 Comparison of GHG Emissions and Energy Demand per Kilometer

In Table 38 the estimated ranges of GHG emissions and primary energy demand for the selected transportation systems are shown.

In Figure 42 the comparison of estimated range of GHG emissions, in Figure 43 of estimated range of cumulated primary energy demand and in Figure 44 estimated range of cumulated fossil primary energy demand for selected transportation systems (2019) in EU 28 is shown.

With current technology the systems using fossil energy in ICE and fuel cell vehicle have high GHG emissions above 150 g CO_2-eq/km. Systems that use a high share of renewable energy have low GHG emissions below 70 g CO_2-eq/km. It is expected with future technologies that all these selected systems have decreasing GHG emissions due to the expected increasing of energy efficiency and higher share of renewable energy. On the longer term perspectives all systems using renewable energy have the potential for very low GHG emissions, where the differences between the systems nearly disappear.

So for the future systems with low GHG emissions the demand of cumulated primary energy becomes more relevant, when the renewable primary energy, which is limited due to sustainability and social issue anyway, should be used most efficiently. The Battery Electric Vehicle with renewable electricity has the lowest primary energy demand, followed by hydrogen and E-fuels.

In Figure 45 the comparison of possible development of estimated average GHG emissions and in Figure 46 for cumulated primary energy demand for selected transportation systems in EU 28 are shown.

Table 38: *Estimated ranges of GHG emissions and primary energy demand for selected transportation systems*

COMPARISON		GHG [gCO_2eq/km]	PED [kWh/km]	PED_{foss} [kWh/km]
ICE_petrol,raw oil,EU28	2019	230 to 240	0.84 to 0.94	0.82 to 0.92
	2030	200 to 210	0.77 to 0.87	0.75 to 0.85
	2050	165 to 175	0.66 to 0.76	0.64 to 0.74
ICE_diesel,raw oil,EU28	2019	185 to 195	0.67 to 0.77	0.65 to 0.75
	2030	165 to 175	0.62 to 0.72	0.60 to 0.70
	2050	135 to 145	0.52 to 0.62	0.51 to 0.61
ICE_CNG,natural gas,EU28	2019	175 to 185	0.78 to 0.88	0.77 to 0.87
	2030	155 to 165	0.70 to 0.80	0.68 to 0.78
	2050	125 to 135	0.46 to 0.56	0.45 to 0.55
ICE_FT-diesel,mix,EU28	2019	52 to 62	1.1 to 1.2	0.13 to 0.23
	2030	40 to 50	0.89 to 0.99	0.14 to 0.24
	2050	27 to 37	0.68 to 0.78	0.10 to 0.20
ICE_CRG,mix,EU28	2019	62 to 72	1.2 to 1.3	0.36 to 0.46
	2030	38 to 48	1 to 1.1	0.29 to 0.39
	2050	19 to 29	0.72 to 0.82	0.19 to 0.29
HFC_H2,natural gas,EU28	2019	170 to 180	0.81 to 0.91	0.76 to 0.86
	2030	120 to 130	0.64 to 0.74	0.59 to 0.69
	2050	84 to 94	0.41 to 0.51	0.37 to 0.47
HFC_H2,wind,EU28	2019	49 to 59	0.85 to 0.95	0.15 to 0.25
	2030	31 to 41	0.69 to 0.79	0.090 to 0.19
	2050	17 to 27	0.53 to 0.63	0.046 to 0.15
ICE_E-fuel FT-diesel,wind&CO2ind,EU28	2019	46 to 56	1.4 to 1.5	0.13 to 0.23
	2030	33 to 43	1.2 to 1.3	0.10 to 0.20
	2050	20 to 30	0.92 to 1	0.050 to 0.15
PHEV_petrol&el,raw oil&el,EU28	2019	175 to 185	0.76 to 0.86	0.68 to 0.78
	2030	135 to 145	0.65 to 0.75	0.56 to 0.66
	2050	100 to 110	0.5 to 0.60	0.42 to 0.52
BEV_electr.,mix,EU28	2019	140 to 150	0.75 to 0.85	0.62 to 0.72
	2030	91 to 100	0.60 to 0.70	0.45 to 0.55
	2050	49 to 59	0.44 to 0.54	0.28 to 0.38
BEV_electr.,wind,EU28	2019	51 to 61	0.43 to 0.53	0.17 to 0.27
	2030	33 to 43	0.36 to 0.46	0.12 to 0.22
	2050	16 to 26	0.27 to 0.37	0.060 to 0.16

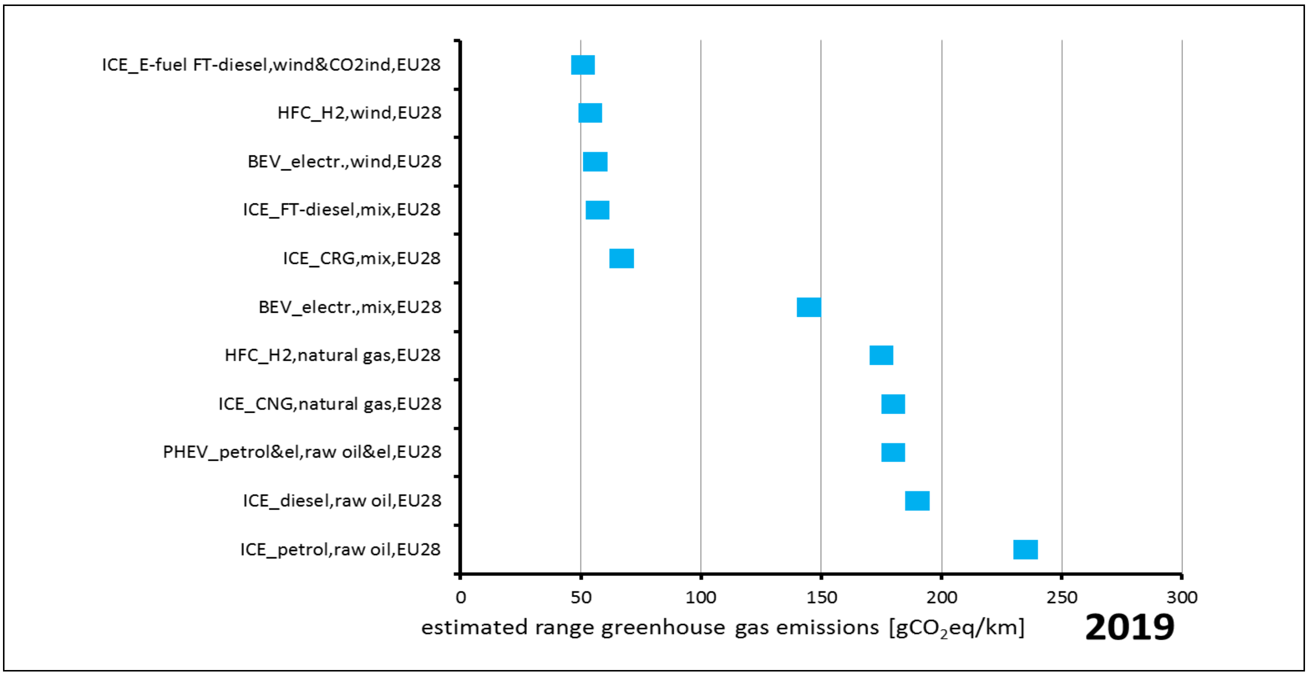


Figure 42: Comparison of estimated ranges of GHG emission for selected transportation systems in 2019 in EU 28

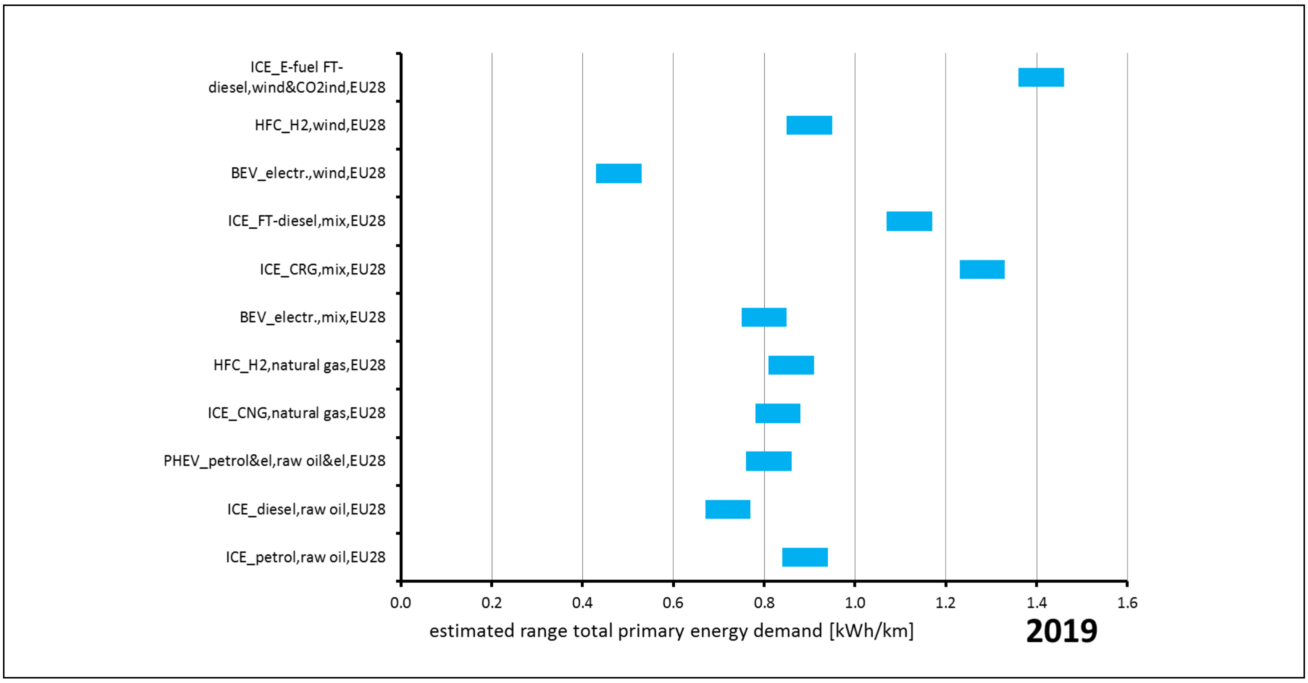


Figure 43: Comparison of estimated ranges of cumulated primary energy demand for selected transportation systems in 2019 in EU 28

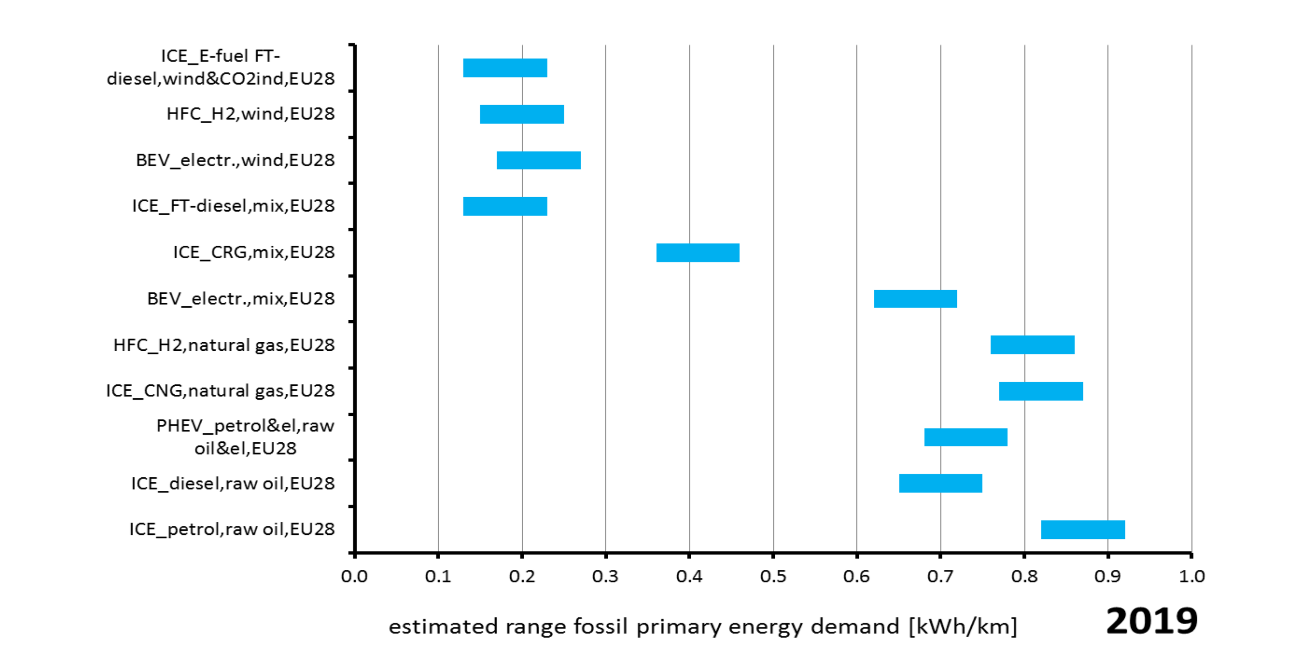


Figure 44: Comparison of estimated ranges of cumulated fossil primary energy demand for selected transportation systems (2019) in EU 28

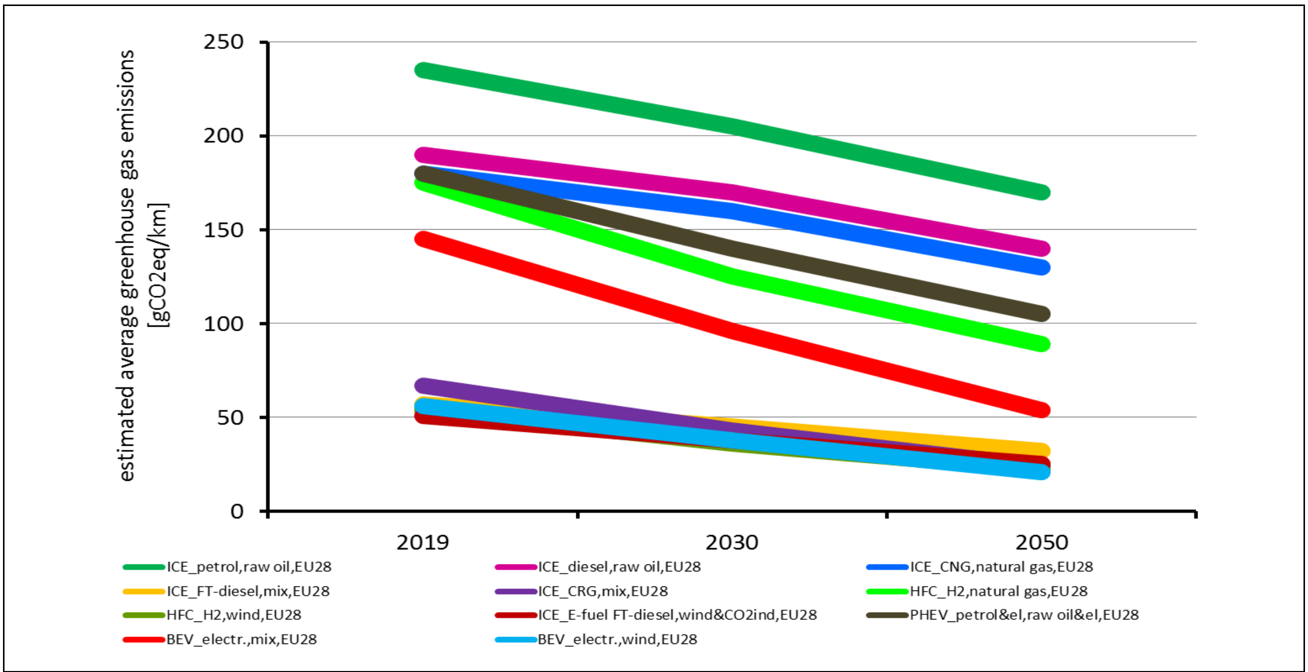


Figure 45: Comparison of possible development of estimated average GHG emissions for selected transportation systems in EU 28

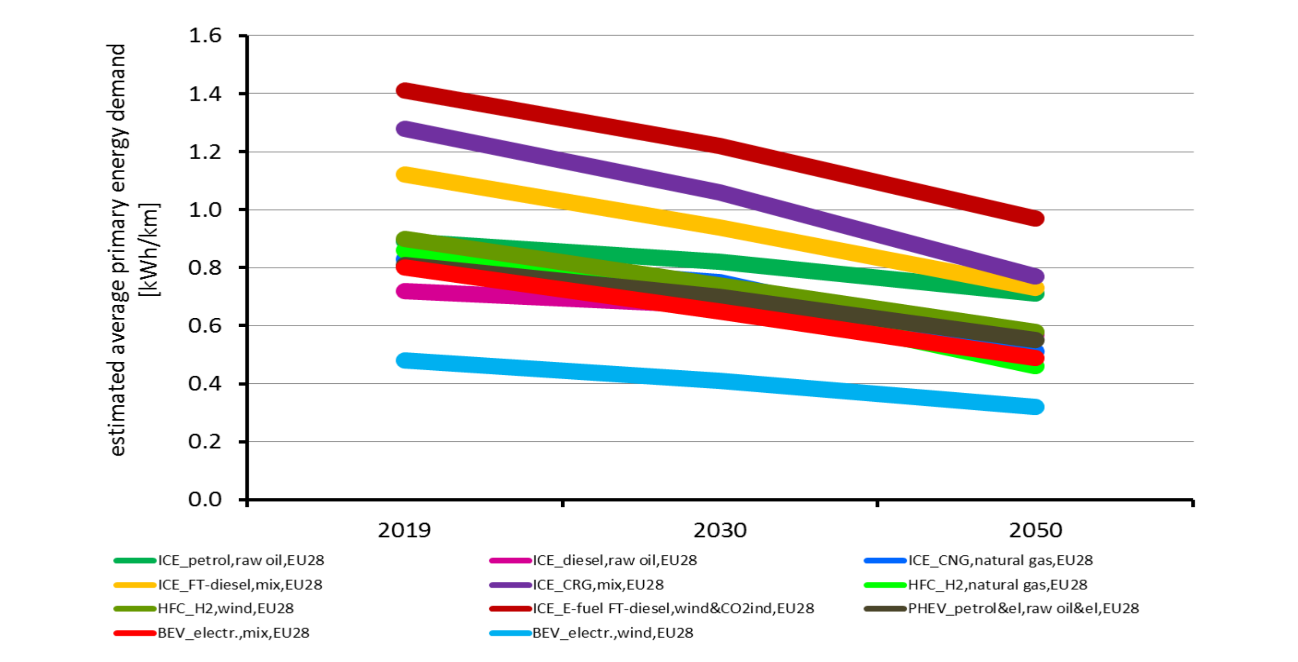


Figure 46: Comparison of possible development of estimated average cumulated primary energy demand for selected transportation systems in EU 28

6.8.2 Comparison of Cumulated GHG Emissions over Lifetime

In Figure 47 the estimated cumulated GHG emissions of Internal Combustion Engine Vehicle (ICEV) using liquid fossil and biogenic fuels are shown. Petrol has the highest cumulated GHG emissions and FT-diesel from wood and straw the lowest GHG emissions. HVO and FAME are more or less between petrol and FT-diesel. All the ICE vehicles have the same GHG emissions from production and end of life. The fuels based on renewable energy have lower GHG emissions during the operation of the vehicle.

In Figure 48 the estimated cumulated GHG emissions of Internal Combustion Engine Vehicle (ICEV) using gaseous fossil and biogenic fuels are shown. CNG has the highest GHG emissions and CRG from a biomass mix the lowest GHG emissions. The blending of 5% of CRG to CNG has a small contribution in GHG saving compared to CNG.

In Figure 49 the estimated cumulated GHG emissions of Hydrogen Fuel Cell Vehicle (HFCV) and Battery Electric Vehicles (BEV) using renewable electricity from wind, hydro and PV in EU 28 are shown. The GHG emissions from the production of the BEV are higher than those of the FCHV, as the battery has higher emissions than the fuel cell. But due to the material recycling of batteries a GHG saving might be reached in the end of life phase of the BEV. The hydrogen vehicle using electricity from PV has the highest cumulated GHG emissions due to the lower energy efficiency during the operation phase of the HFCV compared to the BEV. In case of using electricity from hydro power and wind for FCHV and BEV the cumulated GHG emissions are about the same. For all systems the cumulated GHG emissions from the production phase of the vehicles are about the same or higher than those of the operation phase.

In Figure 50 the estimated cumulated GHG emissions of Internal Combustion Engine Vehicle (ICEV) using liquid biogenic fuels and E-fuels are shown. Due to the lower energy content a conversion efficiency of FT-diesel from wood and straw the GHG emission of the ICEV with FT-diesel is higher than for FT-diesel E-Fuel from wind electricity. For all systems the cumulated GHG emissions from the production phase of the vehicles are about the same or higher than those of the operation phase.

In Figure 51 the estimated cumulated GHG emissions of Internal Combustion Engine Vehicle (ICEV) using gaseous biogenic fuels and E-fuels are shown. The ICEV using CRG from a biomass mix has the highest cumulated GHG emissions and CRG as E-fuel from wind the lowest. In case of CRG as E-fuel the GHG emission from the production phase of the vehicle is higher than those from the operation phase.

In Figure 52 the estimated cumulated GHG emissions of Battery Electric Vehicle (BEV) and Hydrogen Fuel Cell vehicle (HFCV) and ICE Vehicle FT-diesel from biomass and as E-fuel are shown for 2019. All systems have about the same cumulated GHG emissions – except E-fuel using CO_2 from air. Even though the contributions from the production, operation and end –of life phases are quite different.

In Figure 53 the estimated cumulated GHG emissions of selected transportation systems are shown. The cumulated GHG emissions are quite different: systems using a high share of fossil energy e.g. petrol, diesel and E-fuel from current EU28 electricity mix have high GHG emissions, systems with a high share of renewable energy have low GHG emissions, e.g. BEV, E-Fuels and HFCV with renewable electricity, even though the GHG emissions from production phase of these systems might be most relevant in the total life cycle.

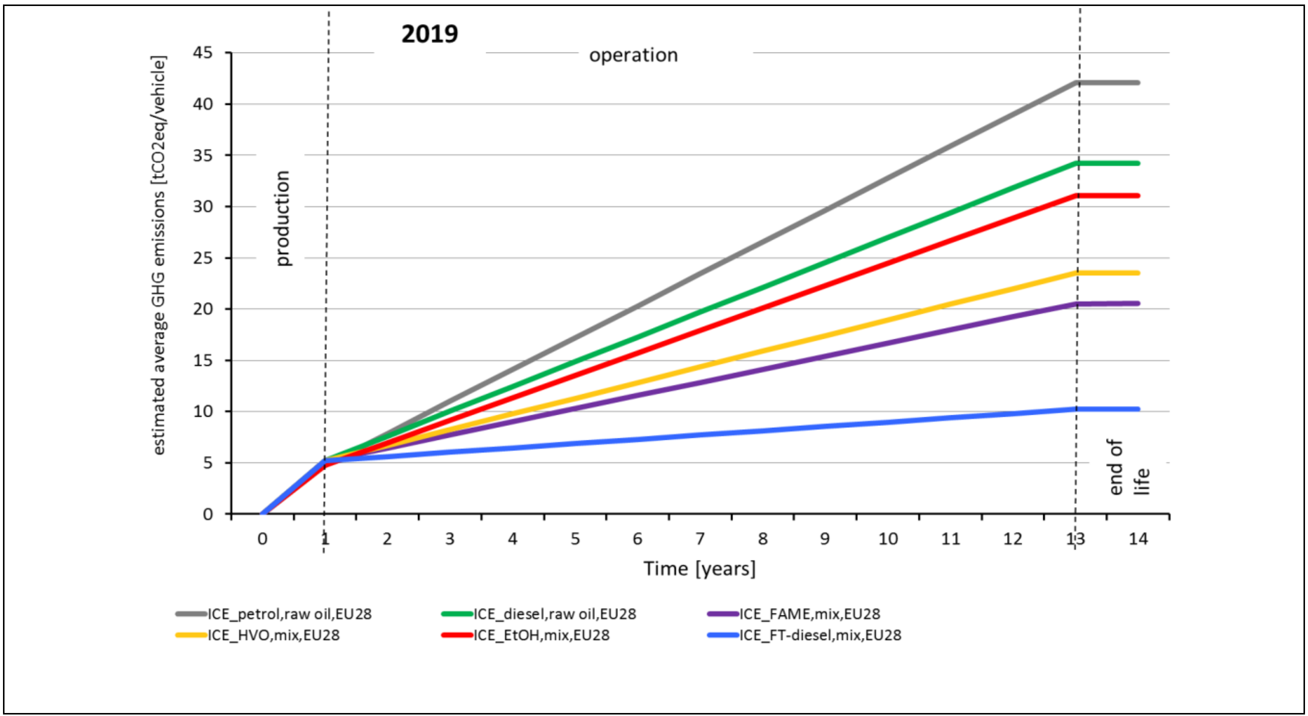


Figure 47: Estimated cumulated GHG emissions of Internal Combustion Engine Vehicle (ICEV) using liquid fossil and biogenic fuels

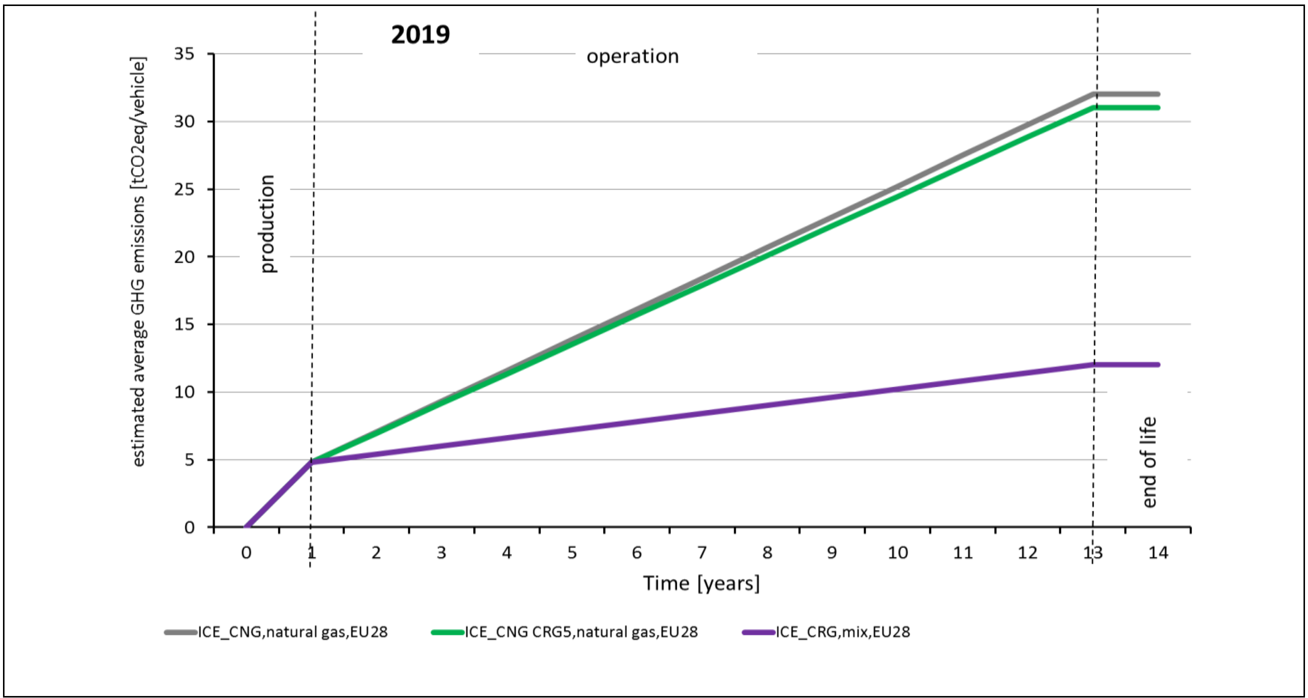


Figure 48: Estimated cumulated GHG emissions of Internal Combustion Engine Vehicle (ICEV) using gaseous fossil and biogenic fuels

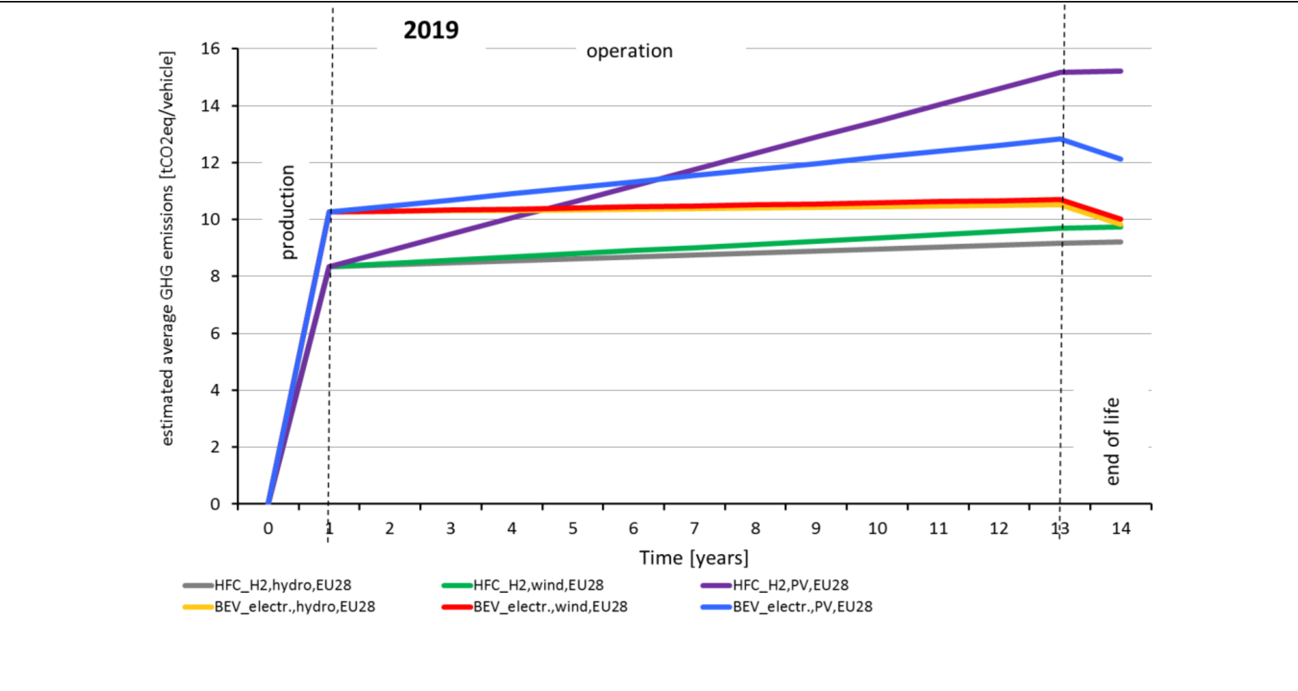


Figure 49: *Estimated cumulated GHG emissions of Hydrogen Fuel Cell Vehicle (HFCV) and Battery Electric Vehicles (BEV) using renewable electricity from wind, hydro and PV in EU 28*

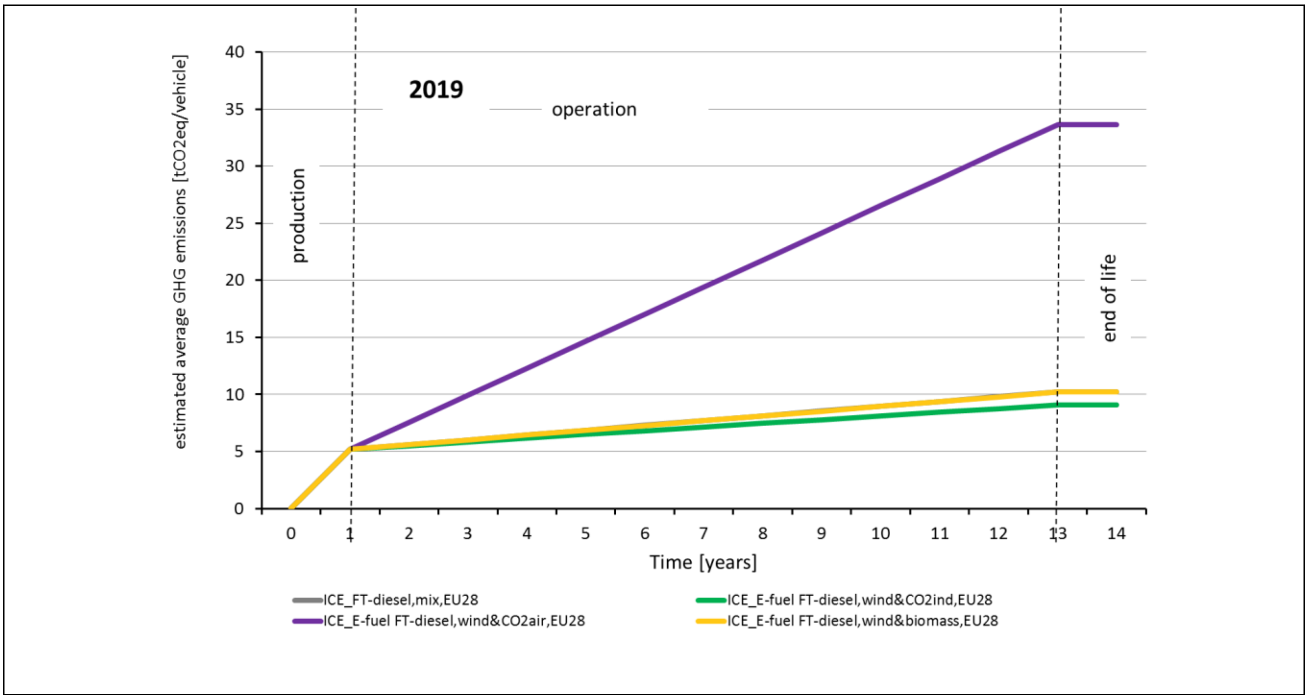


Figure 50: *Estimated cumulated GHG emissions of Internal Combustion Engine Vehicle (ICEV) using liquid biogenic fuels and E-fuels*

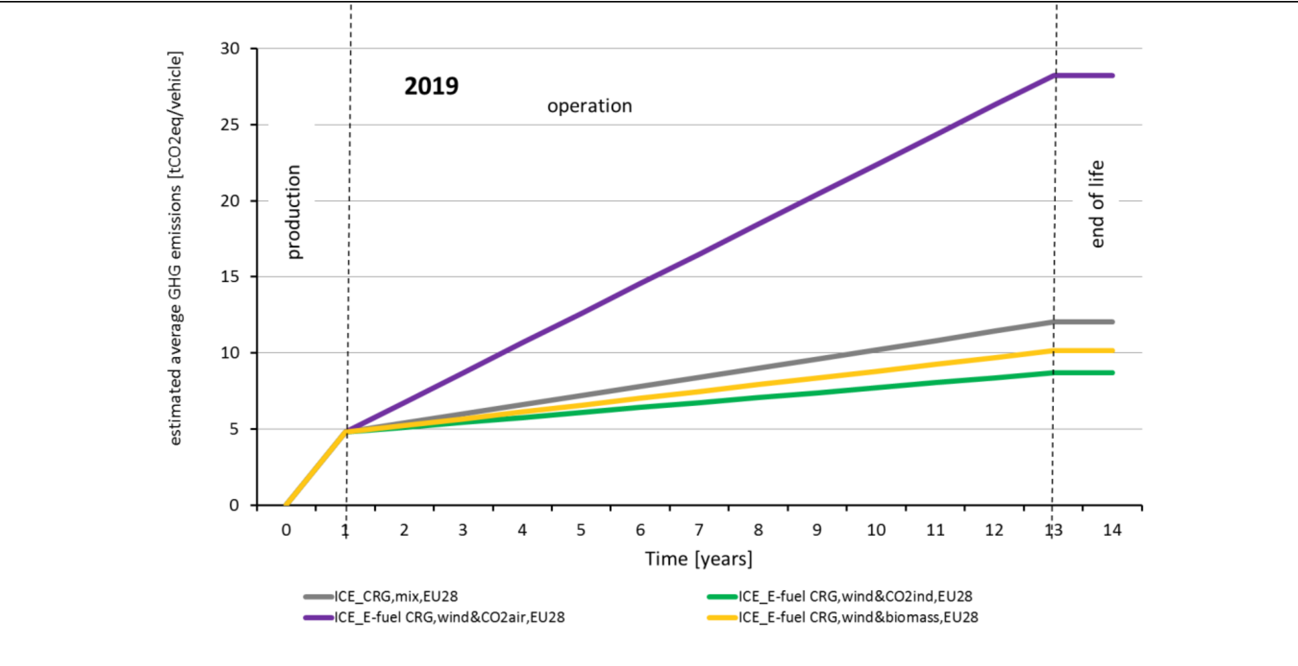


Figure 51: *Estimated cumulated GHG emissions of Internal Combustion Engine Vehicle (ICEV) using gaseous biogenic fuels and E-fuels*

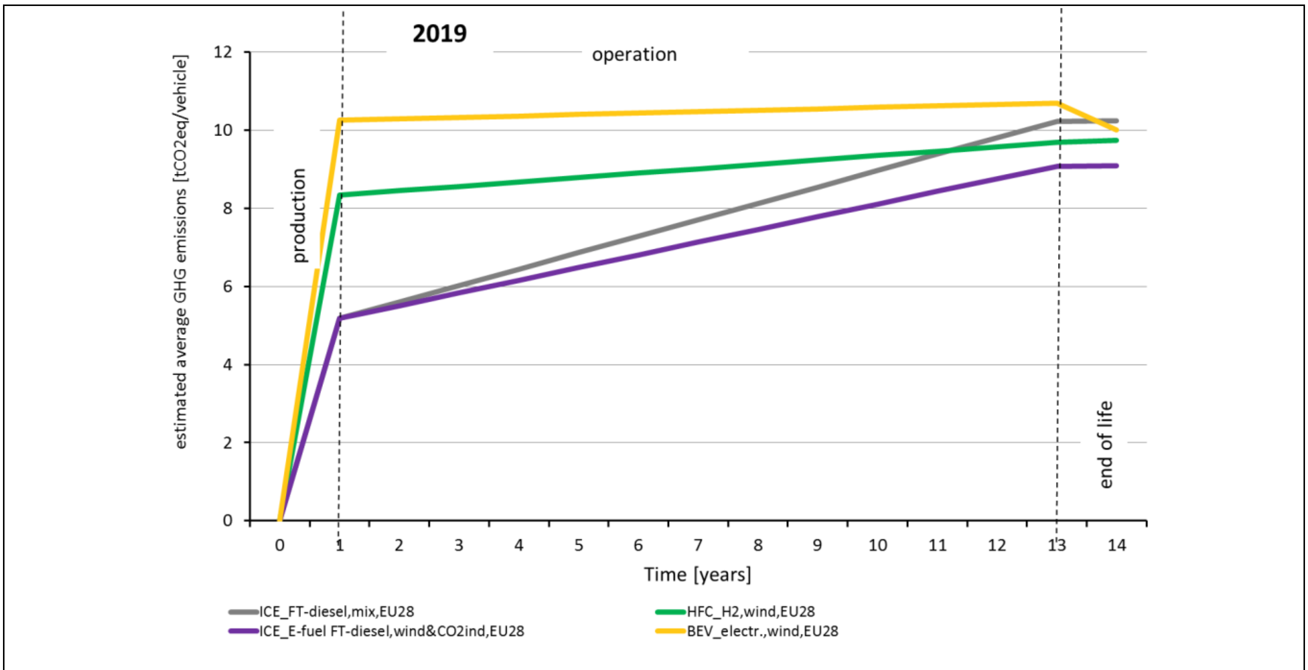


Figure 52: *Estimated cumulated GHG emissions of Battery Electric Vehicle (BEV) and Hydrogen Fuel Cell vehicle (HFCV) and ICE Vehicle FT-diesel from biomass and as E-fuel*

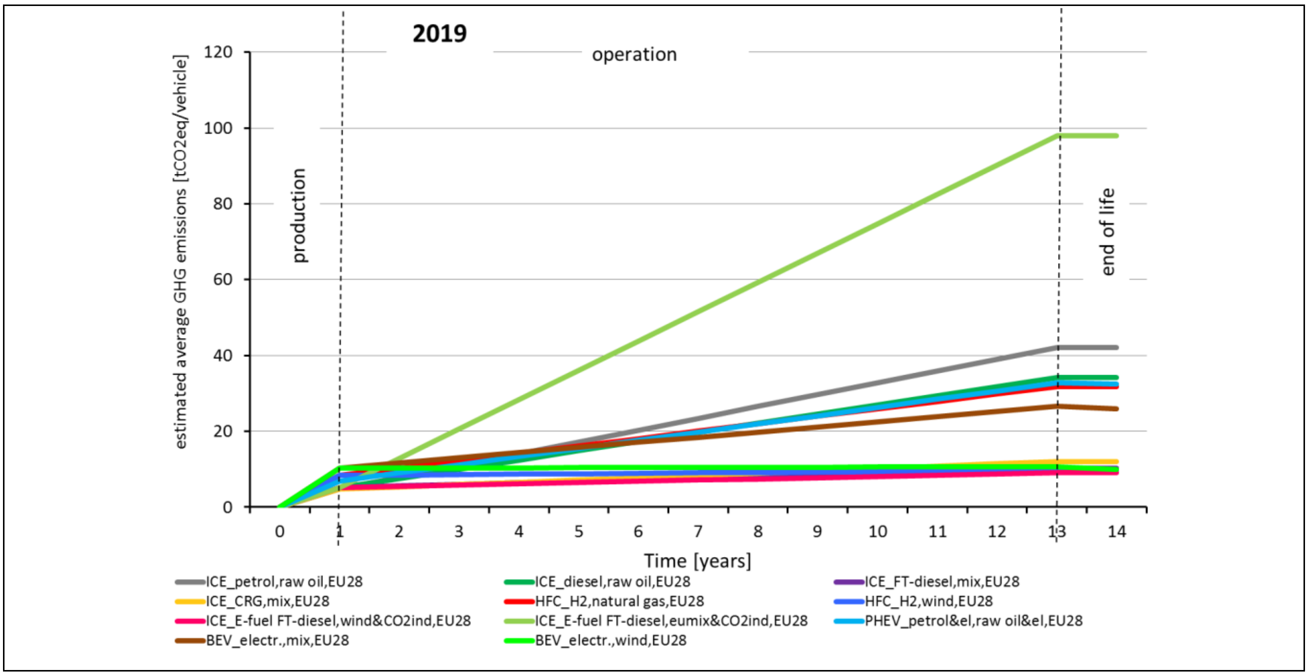


Figure 53: Estimated cumulated GHG emissions of selected transportation systems

7. Main Findings and Conclusions

The main findings of the environmental assessment using LCA for estimating the GHG emission and the cumulated primary energy demand are:

- An environmental assessment can only be done on the basis of Life Cycle Assessment.
- The contribution of the production and the operation phase to the total cumulated environmental effects is quite different and depends on the system under consideration.
- All three types of GHG emissions - CO_2, CH_4 and N_2O – must be considered. CO_2 most relevant for fossil fuels, CH_4 for natural gas, coal and compressed renewable gas and N_2O for biofuels from agricultural crops.
- The GHG emission and the primary energy demand must be assessed separately, as low GHG emissions from using renewable energy are not connected to a high energy efficiency, as fossil fuels are often more energy efficient but have high GHG emissions.
- The fossil primary energy demand is often correlated with the GHG emission, except for biofuels due to the N_2O-emissions from agricultural biomass (e.g. HVO from rape seed) and CH_4-emissions from gaseous fuels, e.g. CNG, CRG.
- The fossil based transport systems e.g. petrol, diesel and CNG have the highest GHG emissions.

- The transportation systems using a (a high share of) renewable energy have low GHG emissions, where in some case the GHG emissions from the production phase might become most dominating.
- Even on the long term perspective there is no “Zero-GHG emission” vehicle possible, but low GHG emission below 25 g CO_2-eq/km are possible assuming further technology development.
- The most relevant parameter for all systems is the energy demand for operating the vehicle. Light and small vehicles and slow driving might also contribute to a low energy consumption of vehicle operation for all considered systems.
- The lifetime of the vehicle and especially of the hydrogen fuel cell and the battery might have a significant influence on the GHG emission from the production phase per kilometer.
- Co-products are of high importance for all biofuels, e.g. animal feed for HVO, FAME and bioethanol; heat for FT-diesel and CRG.
- A relevant co-product of electricity for BEV and PHEV is heat from CHP plants that is or can be used as district heat.
- An increasing use of renewable energy for transportation services leads to decreasing GHG emissions. But as the available additional renewable energy should be used efficient also a low primary energy demand becomes more relevant; as e.g. with the same amount of renewable energy more kilometers might be driven with a BEV than an HFCV or and E-Fuel ICEV.

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9. Annex I: Background Data

9.1 LCA of Battery Production

In this chapter the LCA modelling of battery production is described.

9.1.1 Basic Data

For the LCA based estimation of the GHG emissions and the cumulated primary energy demand of automotive battery systems the following literature was mainly used:

- Ahmed A. et al. (2016). Energy impact of cathode drying and solvent recovery during lithium-ion battery manufacturing. Journal of Power Sources, Volume 322, p. 169-178
- Dai Q. et al. (2017). Update of Life Cycle Analysis of Lithium-ion Batteries in the GREET Model. Argonne National Laboratory. Lemont, USA.
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- Romare M. et al. (2017). The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries. Report. IVL Swedish Environmental Research Institute. Stockholm, Sweden.

9.1.2 LCA Modelling of Automotive Batteries

Based on the literature the system boundaries for the LCA System for automotive battery systems were developed, from raw material and primary energy to the service of the battery, which are shown in *Figure 54*. The main processes are

- Raw material mining and refining
- Grade material production
- Battery system manufacturing
- Battery use
- Reuse
- Recycling and 2nd life (Reuse)
- Transports

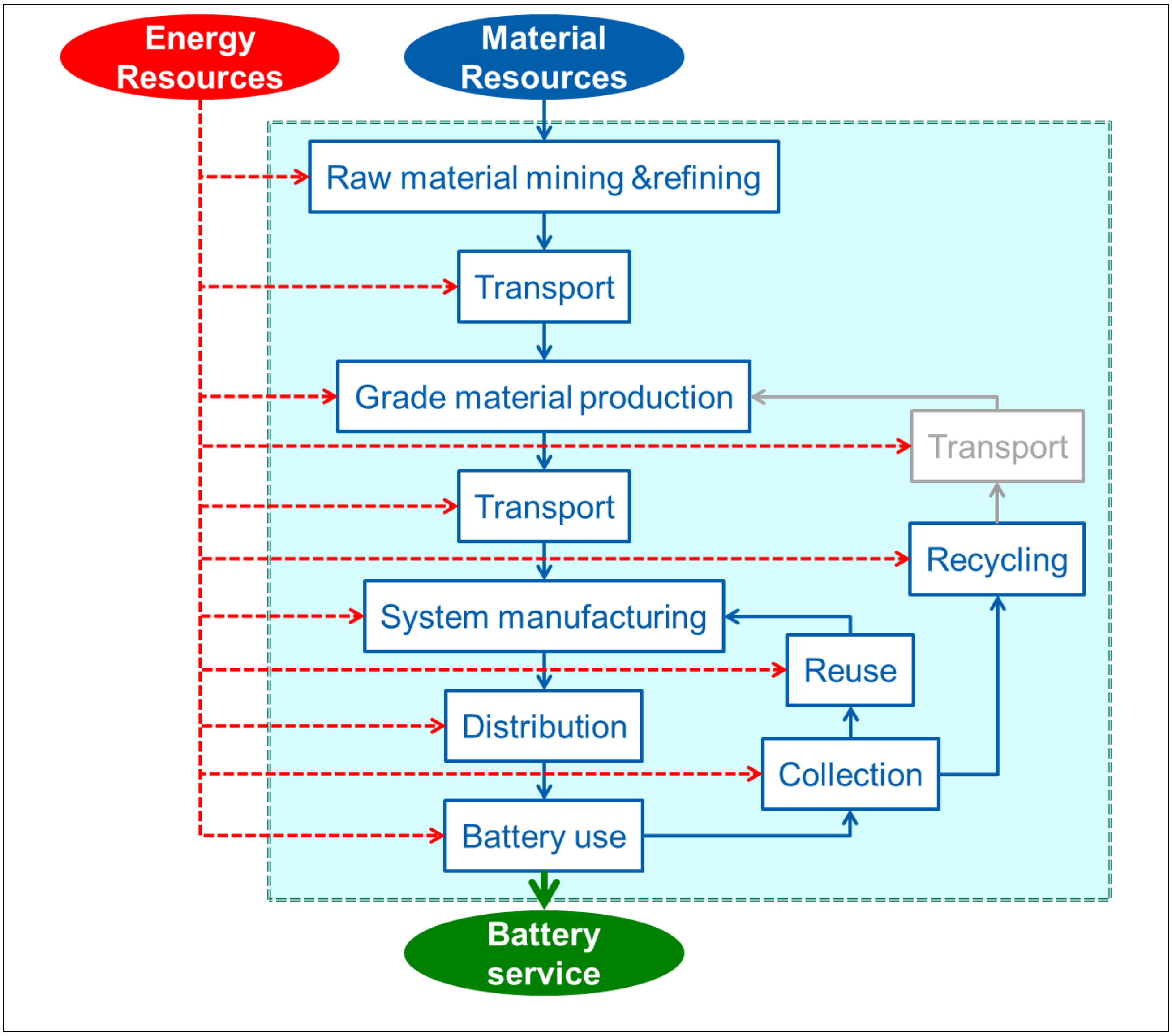

Figure 54: System boundaries for automotive battery systems

The LCA for automotive battery system is done for the following two functional units

- per $kWh_{battery\ capacity}$, e.g. kg $CO_{2\text{-}eq}$/kWh
- per km_{driven} (35 kWh, 150,000 km), e.g. g $CO_{2\text{-}eq}$/km with a passenger vehicle

The modelling of the automotive battery system is done for the following seven main components (*Figure 55*):

1. Cathode

2. Anode

3. Electrolyte
4. Separator
5. Module and battery packaging
6. Battery-Management-System (BMS)
7. Cooling system

The distribution of the total weight to these 7 components is shown in *Figure 56*.

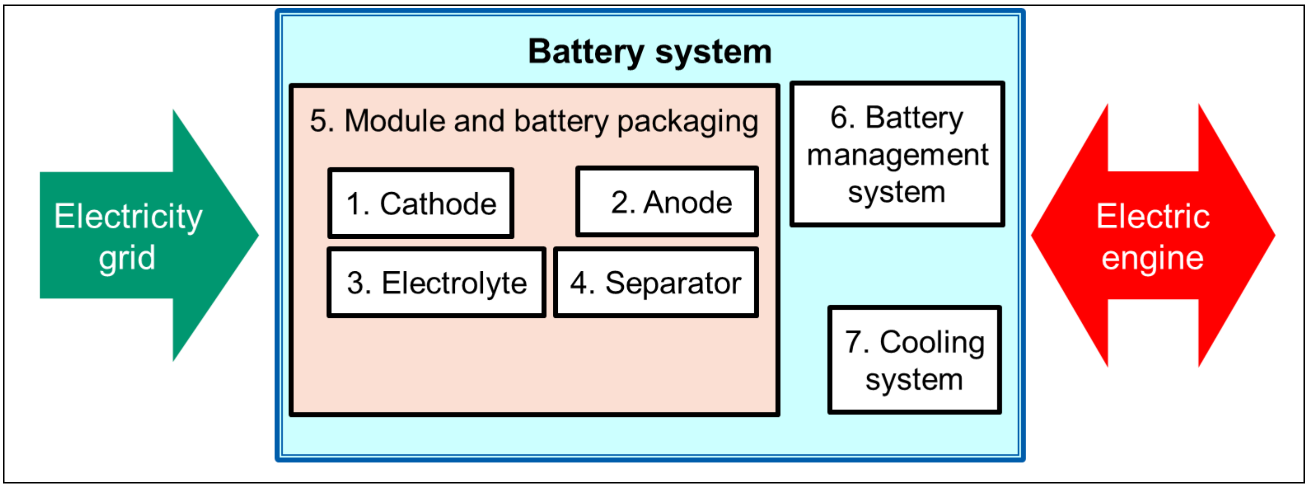

Figure 55: Main components of the automotive battery system

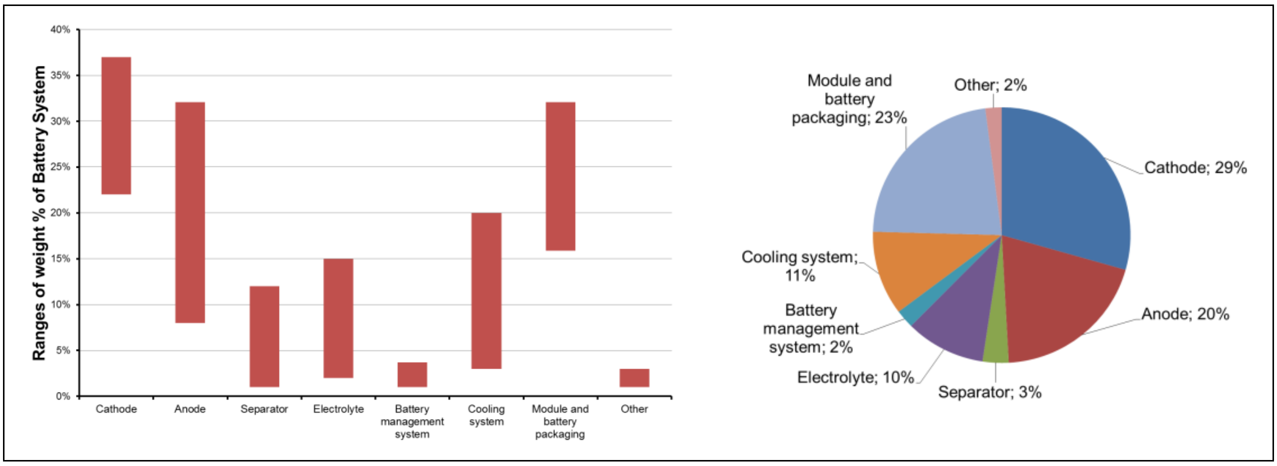

Figure 56: Range and estimated average distribution of the weight of these seven components in the automotive battery system (JOANNEUM RESEARCH 2019)

The following materials of the automotive battery system are considered in the LCA:

- Aluminium
- Cobalt
- Copper
- Graphite
- Lithium
- Manganese
- Nickel
- Plastic
- Steel & Iron
- other

The distribution of these materials in the seven components of the automotive battery system is shown in *Figure 57*.

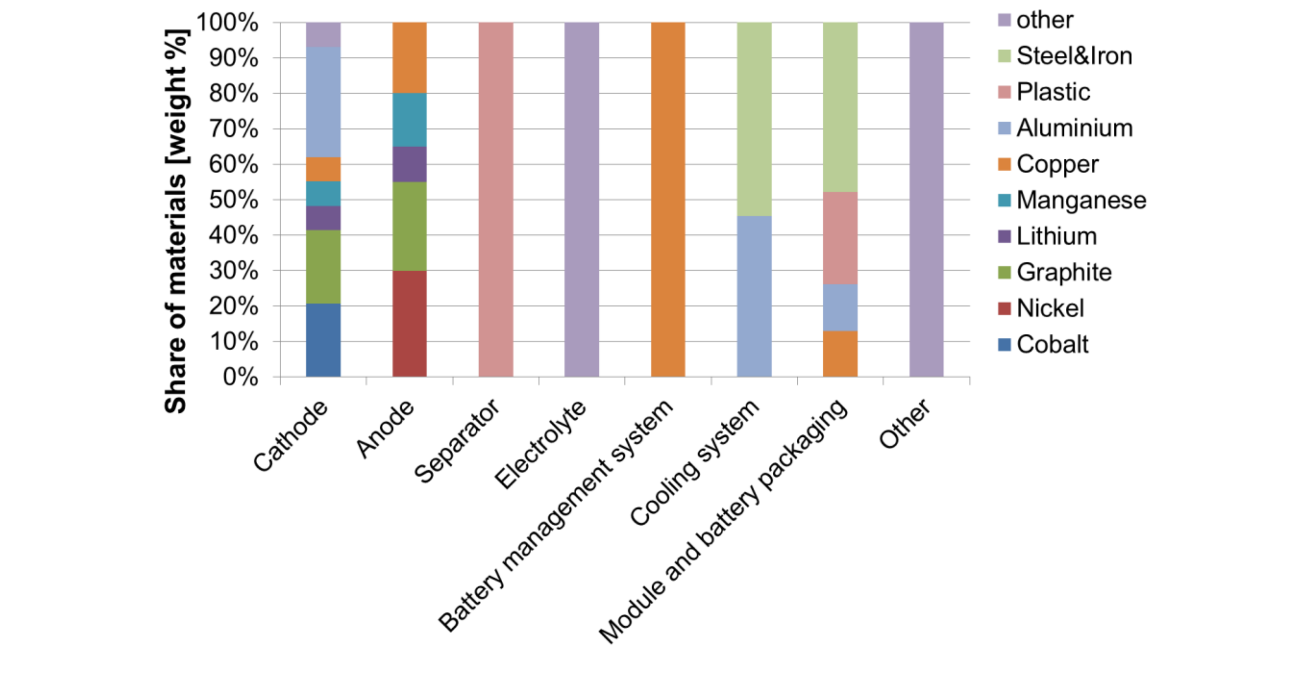

Figure 57: Distribution of materials in the seven components of the automotive battery system (JOANNEUM RESEARCH 2019)

9.1.3 Estimated GHG Emissions and Primary Energy Demand

Based on the mass balance and the environmental effects of the material and energy supply the GHG emissions for the grade material production are estimated based on literature data. In *Figure 58* the range of the estimated GHG emissions of the grade material of automotive battery systems are shown, which is between 25 – 68 kg CO_2-eq/kWh, with an estimated average 46 kg CO_2-eq per kWh battery capacity.

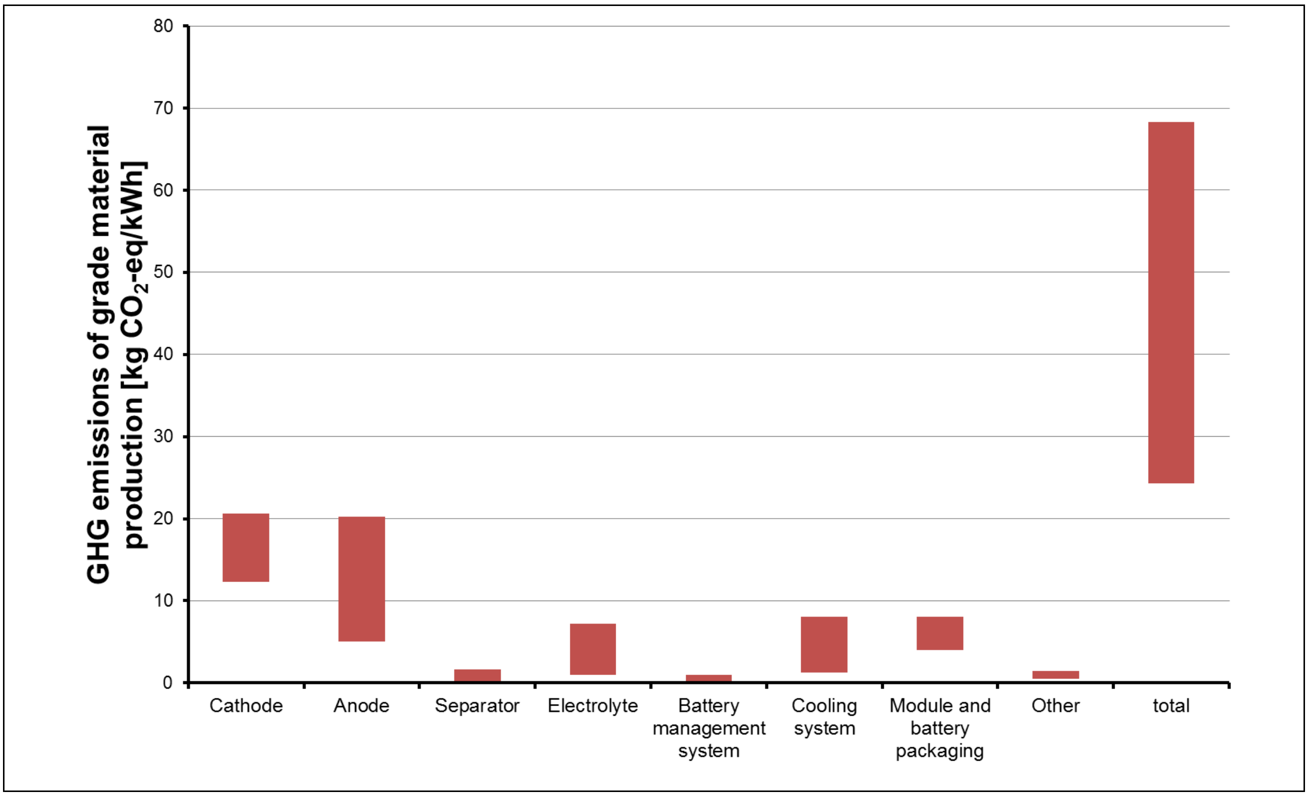

Figure 58: Range of estimated GHG emissions of the grade material production of automotive battery systems (JOANNEUM RESEARCH 2019)

The electricity demand for the manufacturing is quite relevant and is estimated with about 163 kWh/kWh (Romare 2017, Ellingsen 2014), which is used as default value. The location of the battery production determines the electricity mix with its GHG emission and primary energy demand. As default value it was assumed that the battery is produced in Asia with GHG emissions of the electricity with about 700 g CO_2-eq/kWh (calculated from IEA statistics). ARGONNE has published recently (Dai 2017) new data on the energy demand for battery production, which are used in the sensitivity analysis (see chapter 9.1.5 Main Influences).

For the end of life phase of automotive batteries – material recycling or reuse as stationary application in a 2nd life –are less data available. The battery recycling is currently tested in pilot and demo plants as a combination of mechanical and pyro- and hydrometallurgical processes. For the LCA modelling the following assumptions are used

- Dismantling of the battery module with use of aluminium and plastics
- Dismantling of the battery cells with use of copper and aluminium

- Dismantling of the cathode with use of aluminium and
- Hydrometallurgical recycling of cobalt and nickel.

The recycling rate for the materials is assumed to be 65%, and for these secondary materials credits from primary material production are given. The energy demand for recycling was estimated (based on Romare 2017). For using the battery for a 2nd stationary life it was assumed that about 50% of the automotive battery is used in a 2nd life, where the best cells are tested and reassembled again.

In Figure 59 the average estimated GHG emissions of automotive battery systems are shown using the modelling assumption as described above. The influence of the energy demand for production has a significant influence on the estimated GHG emissions from automotive batteries, which is in total about 171 kg $CO_{2\text{-eq}}$ with recycling and 95 kg $CO_{2\text{-eq}}$ with 2nd stationary life per kWh battery capacity. The influence from recycling is low as the GHG emission for recycling are in about the same order of the credits for the recycled materials, whereas the influence of 2nd life is quite high, as about half of the GHG emissions are allocated to the 2nd life.

In Figure 60 the estimated average cumulated primary energy demand of the automotive battery systems is shown, which is about 561 kWh of primary energy with recycling and 311 kWh of primary energy with 2nd stationary life per kWh battery capacity.

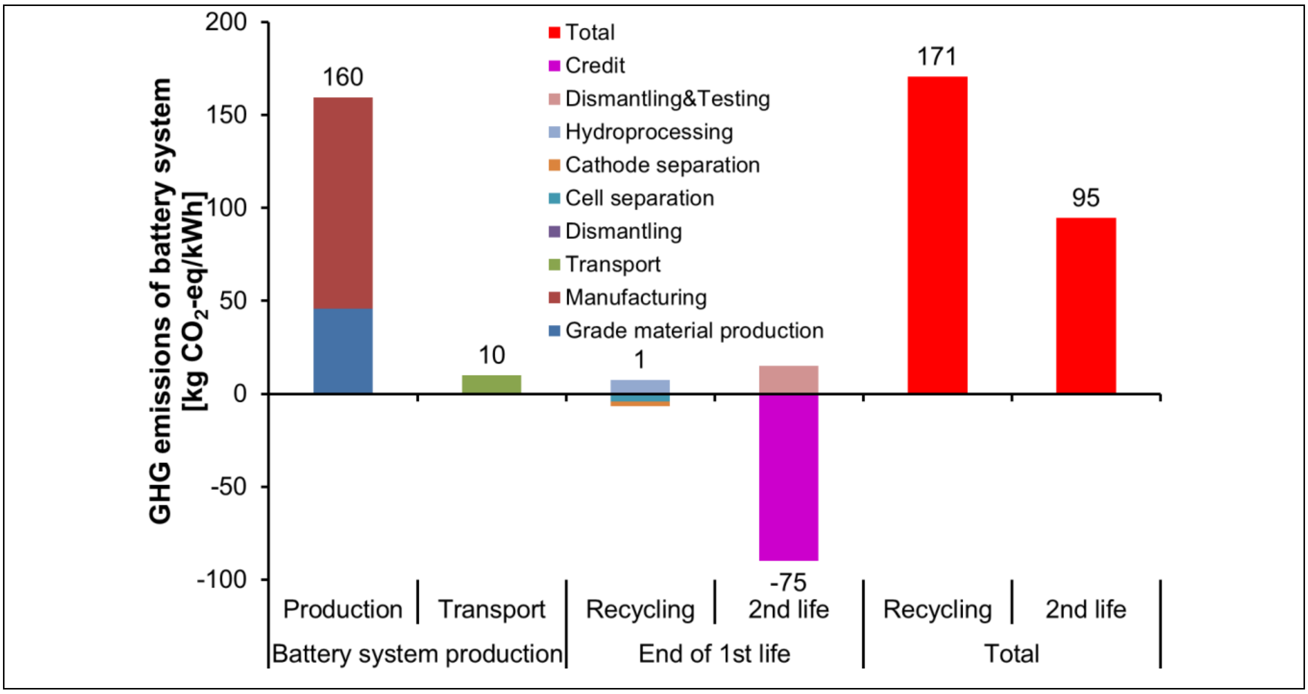

Figure 59: Estimated average GHG emissions of automotive battery systems (JOANNEUM RESEARCH 2019)

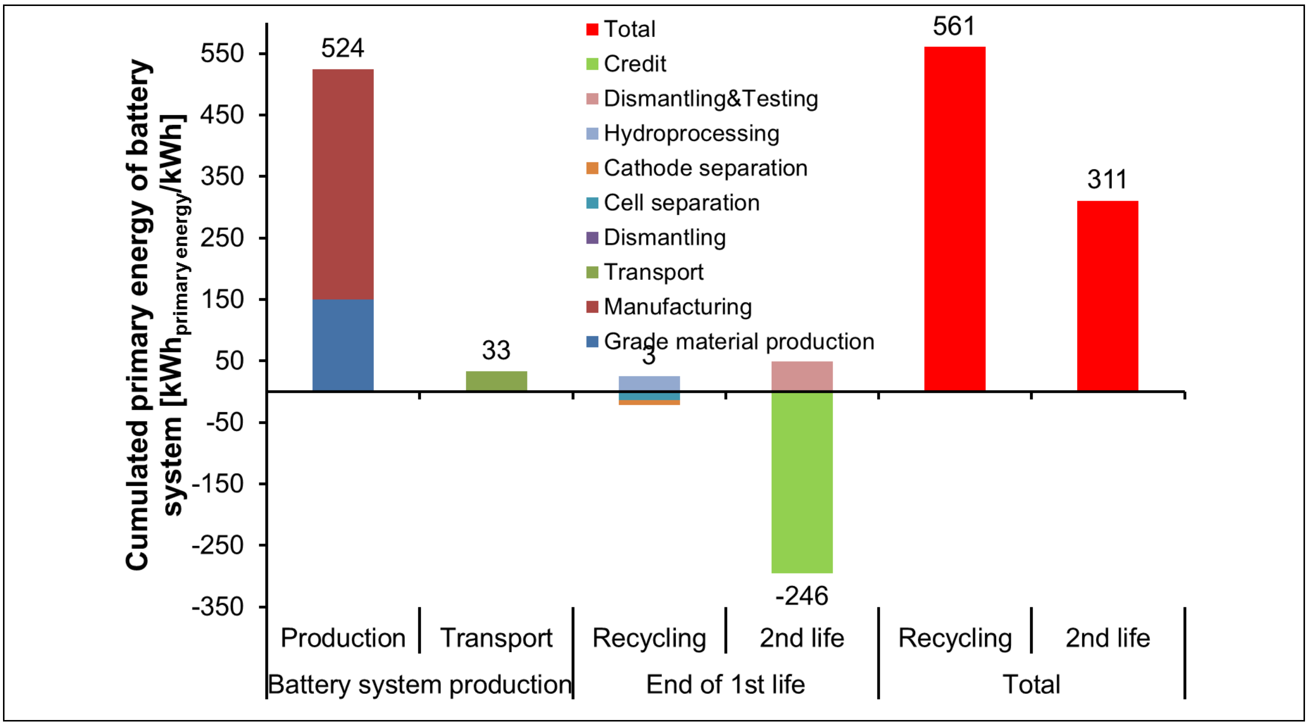

Figure 60: Estimated average cumulated primary energy demand of automotive battery systems(JOANNEUM RESEARCH 2019)

9.1.4 Comparison to Other Studies

Currently the most relevant international meta studies on GHG emissions from automotive battery are the following:

1. *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries*, study from ivl Sweden (Romare 2017) and
2. *Effects of Battery manufacturing on Electric Vehicle Life cycle GHG emissions*, briefing document from ICCT (ICCT 2018)

The comparison of the GHG emissions per battery capacity shows.

- ivl: 175 (150 - 200) kg CO_2-eq/kWh
- ICCT: 175 kg CO_2-eq/kWh
- JOANNEUM:
  - Recycling: 171 kg CO_2-eq/kWh
  - 2nd life: 95 kg CO_2-eq/kWh

and per driven kilometer assuming an average battery capacity and lifetime

- ICCT: 35 g CO_2-eq/km
- JOANNEUM:
  - Recycling: 39 g CO_2-eq/kWh
  - 2nd life: 22 g CO_2-eq/kWh

9.1.5 Main Influences

Reflecting the above modelling and its assumptions the following main influences and uncertainties on the environmental effects of automotive battery systems are identified

- Battery capacity per vehicle (kWh per vehicle) (*Figure 61*)
- Lifetime of battery (km) (*Figure 62*)
- Electricity mix for battery production (g CO_2-eq/kWh of electricity) (*Figure 63*)

- Energy demand for battery production (kWh per kWh battery capacity) (*Figure 64*)

The energy demand for battery production is assumed in average 163 kWh electricity per kWh battery capacity (based on Romare 2017, Ellingsen 2014). Recent studies estimated the energy demand for battery production on commercial big scale significant lower down to 16 kWh/kWh (Dai 2017, Ahmed 2016), which might be realized in future Giga-size battery production systems.

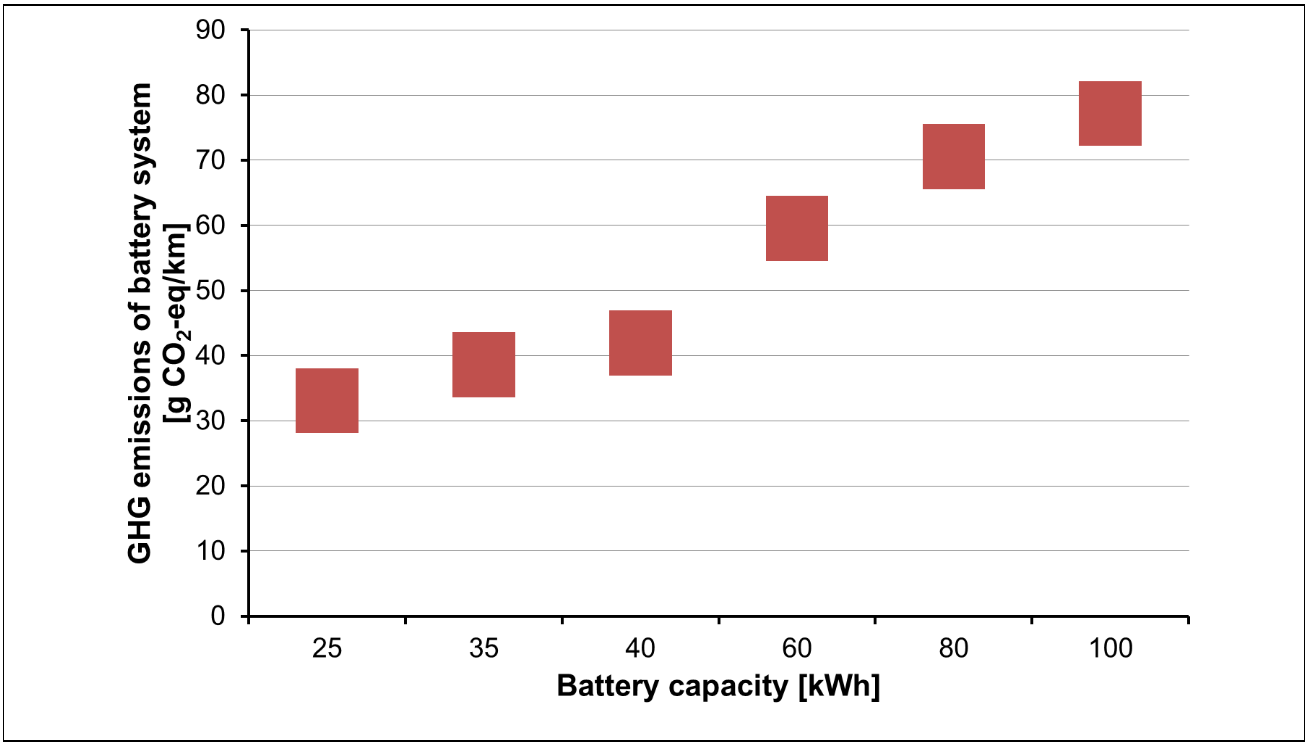

Figure 61: Influence of battery capacity on the estimated range of GHG emissions (JOANNEUM RESEARCH 2019)

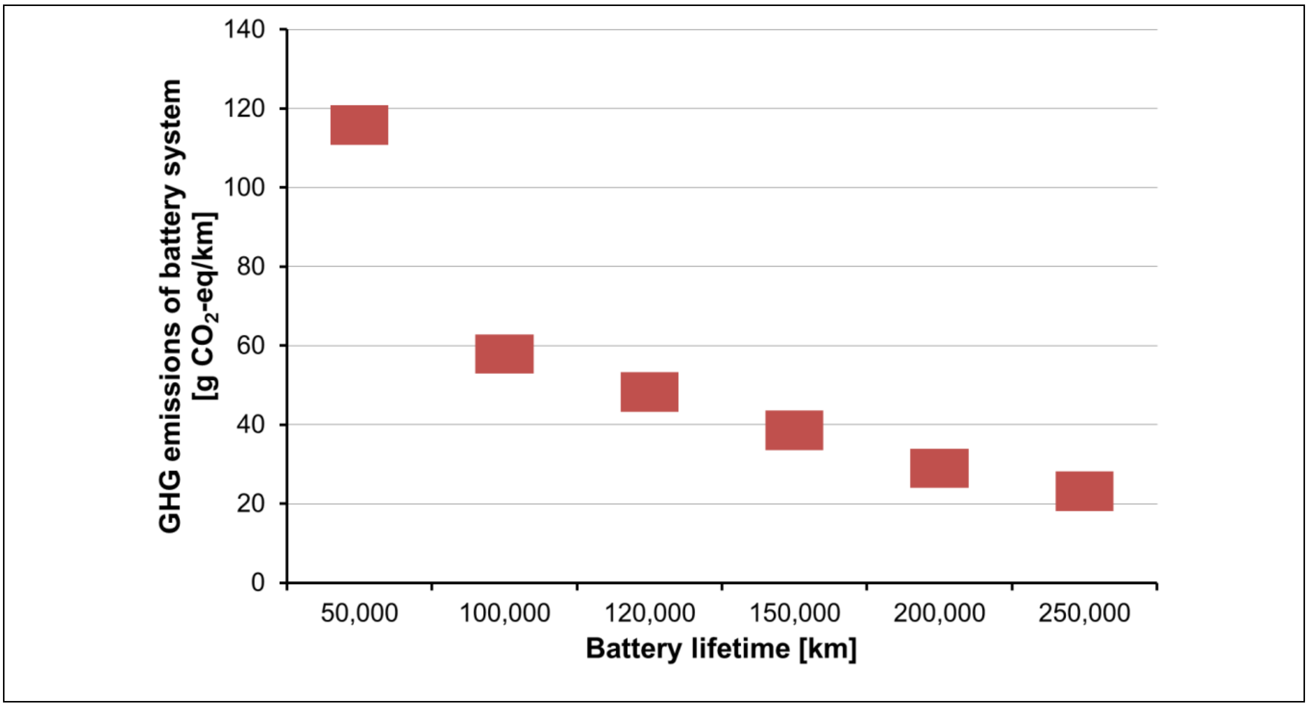

Figure 62: Influence of battery lifetime on the estimated range of GHG emissions (JOANNEUM RESEARCH 2019)

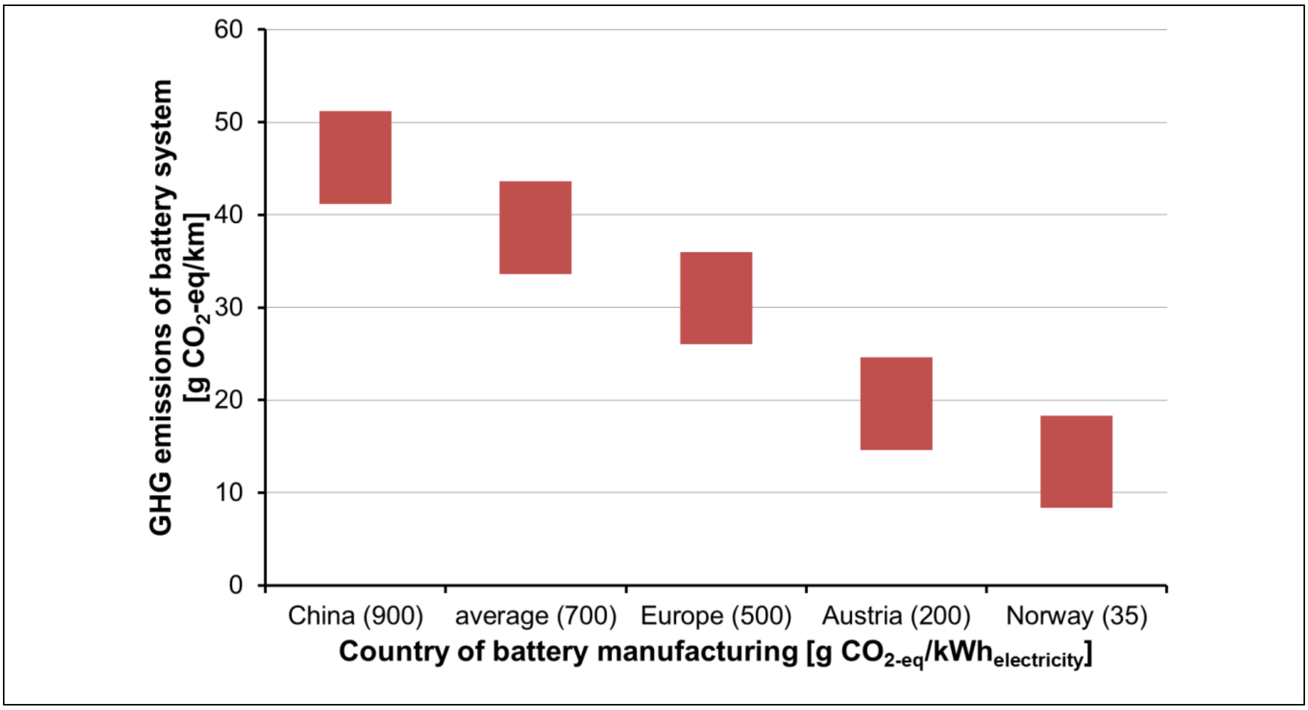

Figure 63: Influence of country specific electricity mix for battery production on the estimated range of GHG emissions (JOANNEUM RESEARCH 2019)

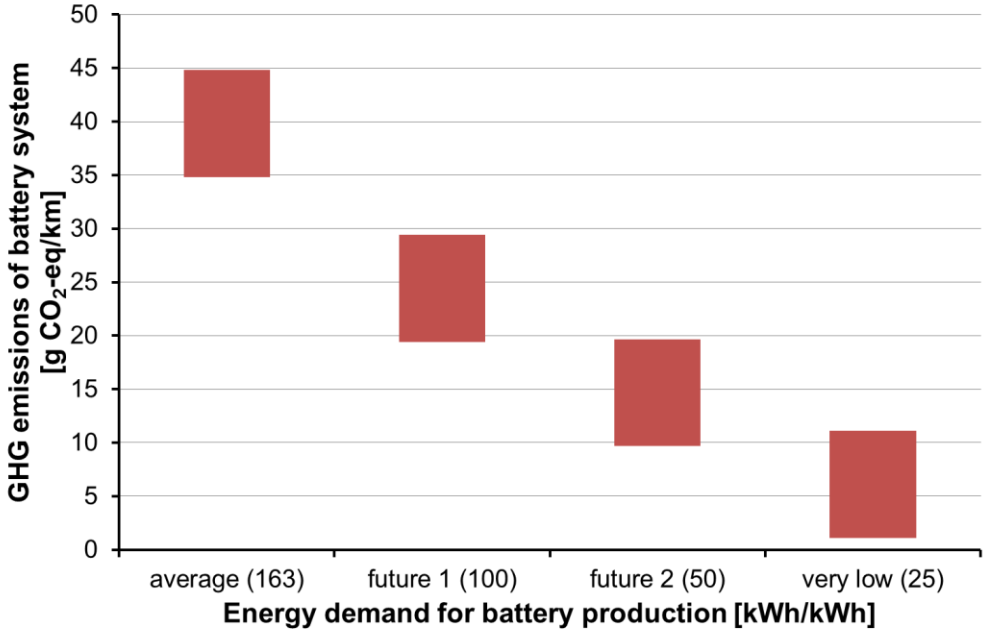

Figure 64: Influence of energy demand for battery production on the estimated range of GHG emissions (JOANNEUM RESEARCH 2019)

9.2 Hydrogen Production

In *Table 39* the main data for hydrogen production via electrolysis and natural gas steam reforming are shown. The oxygen and heat from electrolysis is not used. The electricity demand for the compression and cooling of hydrogen is 2.7 kWh/kg H_2, which is based on the ionic compressor IC 90 of Linde Gas.

Table 39: Data for hydrogen production via electrolysis and natural gas steam reforming (based on JOANNEUM RESEARCH 2019, BioGrace 2015)

		electrolyses	steam reforming
Output			
H2 30 bar	[MWh]	1	1
Input			
electricity	[MWh]	1.67	
natural gas	[t]		0.086

9.3 E-Fuels Production

E-Fuels are produced from a carbon source and hydrogen. The hydrogen is produced via electrolysis with electricity and the carbon, which is derived from the air, a flue gas or biomass.

The formula for the production of compressed renewable gas is:

$$CO_2+4\ H_2=CH_4+2\ H_2O$$

The two formulas for the production of FT-diesel are:

$$CO_2 + H_2 = CO + H_2O$$

$$CO+2\ H_2=CH_2+H_2O$$

In Table 40 the main data for CO_2 capture from flue gas and air are shown. In Table 41 the main data for FT and CRG production from biomass, hydrogen and Carbon dioxide are given. In the LCA the co-produced heat substitutes district heat from the same raw material and resource as the E-fuel.

Table 40: Data for CO_2 capture from flue gas and air (based on JOANNEUM RESEARCH 2019)

		flue gas	air
Output			
CO2	[t]	1	1
water	[t]		1
Input			
electricity	[kWh]	80	700
heat	[kWh]		2,200
MEA (Monoethanolamine)	[kg]	0.01	

Table 41: *Data for FT and CRG production from biomass, hydrogen and Carbon dioxide (based on JOANNEUM RESEARCH 2019)*

		Mix wood & straw	CO2 & hydrogen	Straw, wood & hydrogen	Mix wood & straw	CO2 & hydrogen	Straw, wood & hydrogen
		FT-diesel			CRG		
Output							
fuel	[MWh]	1	1	1	1	1	1
heat as coproduct	[kWh/kWh$_{pr}$	0.2	0.1	0.1	0.2	0.1	0.1
Input							
raw materials	[t]	0.54		0.54	0.45		0.45
	[MWh]	2.00		2.00	1.67		1.67
electricity	[kWh]		15	50		15	50
H2	[MWh]	0.06	1.36	1.25		1.23	1.25
CO2	[t]		0.30			0.20	
Nickel	[kg]				0.0032	0.008	0.0112
Cobald	[kg]	0.001	0.0025	0.0035			

9.4 Biofuel Production

In *Table 42* the main data for vegetable oil production are given. The co-produced animal feed substitutes soy feed. In *Table 43* the main data for FAME (biodiesel) production are shown. The coproduced glycerin substitutes synthetically produced glycerin and the coproduced potassium substitutes for synthetic fertilizer.

In *Table 44* the main data for HVO production are shown. The coproduced electricity substitutes the European grid mix. The coproduced heat substitutes district heat from wood chips.

In *Table 45* the main data for bioethanol production are shown. The coproduced animal feed substitutes soy feed.

In *Table 46* the main data for biogas production are given, the heat derives from the CHP plant using biogas. The electricity demand for the upgrading of biogas to CRG (biomethane) is about 40 kWh per MWh of CH_4.

Table 42: Data for vegetable oil production (based on JOANNEUM RESEARCH 2019, BioGrace 2015)

		rape seed	soy bean	palm oil
Output				
vegetable oil	[MWh]	1	1	1
animal feed	[t]	0.13	0.22	
Input				
raw material	[t]	0.25	0.32	0.65
electricity	[kWh]	11.1	33	0*)
heat	[kWh]	50	160	0*)
fuller's earth	[kg]	0.59	0.59	0.002
phosphoric acid	[kg]	0.10	0.11	0.001
hexane	[kg]	0.25	0.11	0

**) provided internally by CHP plant from processing residues*

Table 43: Data for FAME (biodiesel) production (based on JOANNEUM RESEARCH 2019, BioGrace 2015)

		amount
Output		
FAME	[MWh]	1
glycerine	[kg]	10
potassium (as fertilizer)	[kg]	0.64
Input		
vegetable oil	[t]	0.10
electricity	[kWh]	8.1
heat	[kWh]	66.1
methananol	[kg]	11.4
potassium hydroxide	[kg]	1.0
sulfuric acid	[kg]	1.0
phosphoric acid	[kg]	0.3
NaOH	[kg]	0.7
activated carbon	[kg]	0.1
N2 (liquid)	[kg]	0.2

Table 44: *Data for HVO production (based on JOANNEUM RESEARCH 2019, BioGrace 2015)*

		amount
Output		
HVO	[MWh]	1
electricity	[kWh]	2.1
heat	[kWh]	11.1
Input		
vegetable oil	[t]	0.10
hydrogen	[kWh]	120

Table 45: *Data for bioethanol production (based on JOANNEUM RESEARCH 2019, BioGrace 2015)*

		wheat	maize (corn)	sugar beet	sugar cane	wood	straw
Output							
bioethnaol	[MWh]	1	1	1	1	1	1
animal feed (DDGS)	[kg]	131	121	78			
electricity	[kWh]				0.05	235	214
Input							
raw material	[t]	0.42	0.55	1.62	1.97		0.63
electricity	[kWh]	64	62	47			
heat	[kWh]	450	436	614			
NaOH	[kg]	0.3	0.3	0.3			
ammonia (25%)	[kg]	0.9	0.9	1.1		19	12
sulfuric acid	[kg]	0.3	0.3	0.4		13	5
urea	[kg]	0.1	0.1	0.1			
molasses 880% DM)	[kg]					9	6
Corn Steep Liquor (CSL)	[kg]					25	22
Diammoniahosphate (NH4)2HPO4	[kg]					3	3

Table 46: *Data for biogas production (based on JOANNEUM RESEARCH 2019, BioGrace 2015)*

		maize, gras & residues	residues
Output			
biogas (54% CH_4)	[MWh]	1	
biogas (62% CH_4)			1
fertilizer as coproduct	[t]	0.83	0.61
Input			
raw material	[t]	0.86	0.63
electricity	[kWh]	29	23.6
heat	[kWh]	313	45
diesel	[kWh]	2.9	2.4

9.5 Energy demand and emissions of passenger vehicles

9.5.1 Introduction

For the calculation of the energy demand and the emissions of the passenger vehicles with the different propulsion systems and energy carriers the Simulation Program PHEM - Passenger vehicle and Heavy duty Emission Model – of the Institute of Combustion Engine and Thermodynamics of the Graz University of Technology was used (https://www.fvt.at/em/phem.html). The simulations were done by the Graz University of Technology (Hausberger et al. 2018) for the current state of technology.

The results of the simulations were the

- Energy consumption for driving, heating, cooling and auxiliary services and
- CH_4- and N_2O-emission of the vehicles.

The CO_2-emissions were calculated based on the content of fossil carbon in the liquid or gaseous fuels.

In the following the

- Simulationtool PHEM,
- Vehicle data in PHEM,
- Driving cycle, and
- Emission maps in PHEM

are described.

9.5.2 Simulation Tool PHEM

The PHEM simulation tool was developed by Graz University of Technology (TU Graz) in cooperation with Forschungsgesellschaft für Verbrennungskraftmaschinen und Thermodynamik (FVT). PHEM is a detailed model for 1 Hz simulation of single motor vehicles and vehicle fleets.

The model features are:

- Vehicle longitudinal dynamics simulation using a "backward" approach

- Engine emission behaviour characterised by "emission maps" via engine speed and power
- Additional model elements for exhaust aftertreatment simulation (e.g. SCR, NSC), electrified powertrains (HEV, PHEV, EV) and emission behaviour in transient conditions
- Time resolution: 1 Hz
- HBEFA "average-vehicles" are provided in the corresponding PHEM data package
- Main model output: fuel consumption, CO_2 and pollutant emissions
- Interface to micro-scale traffic models (e.g. VISSIM, Aimsun)

The typical model applications are

- Used for elaboration of HBEFA emission factors for passenger vehicles, light commercial vehicles and heavy duty vehicles. Implementation of two-wheelers in progress for HBEFA.
- Using HBEFA "average vehicles" for generation of emission factors for special local conditions (user defined data on driving cycles, road gradient, ambient conditions, special fleet mix)
    - Example: Comparison of vehicle emissions for speed limit 30 km/h vs. 50 km/h from measured velocity trajectories
- Research and engineering tool
    - Example: simulation of thermal conditions in the exhaust system for layout of waste heat recovery systems
- Link with micro-scale traffic models (e.g. VISSIM, Aimsun)
    - Examples: Traffic light optimisation, high quality air quality modelling
- Academic use (teaching)

The software is distributed as executable code and a license file to run PHEM on two computers. PHEM has a huge data base for different cars, HDV and LDV from which also input fields for the "average" vehicle categories were elaborated. Data files can be provided for the following vehicle categories:

- Passenger vehicles (diesel, petrol, EURO 0 to EURO 6d)
- Light Duty Vehicles (diesel, petrol, EURO 0 to EURO 6)
- Heavy Duty Vehicles (diesel, EURO 0 to EURO VI, split into weight categories)
- Buses
- Coaches

PHEM is a longitudinal dynamics program, which calculates the demand of propulsion power per second for a given driving cycle (speed over time). With the calculated power and engine speed the emission are calculated using engine emission maps. Electric engines in electric propulsion systems are calculated using loss maps. The losses of charging and discharging of batteries are calculated using internal resistance and SOC (state of charge) depending terminal voltage.

In *Figure 65* the scheme of the simulation in PHEM is shown. The input data are given by the driving cycle, the data on vehicle and propulsion, the maps of emissions of internal combustion engine stand losses for electric engines. In *Table 47* the characteristics of fuels used in PHEM simulations are shown based on EUCAR.

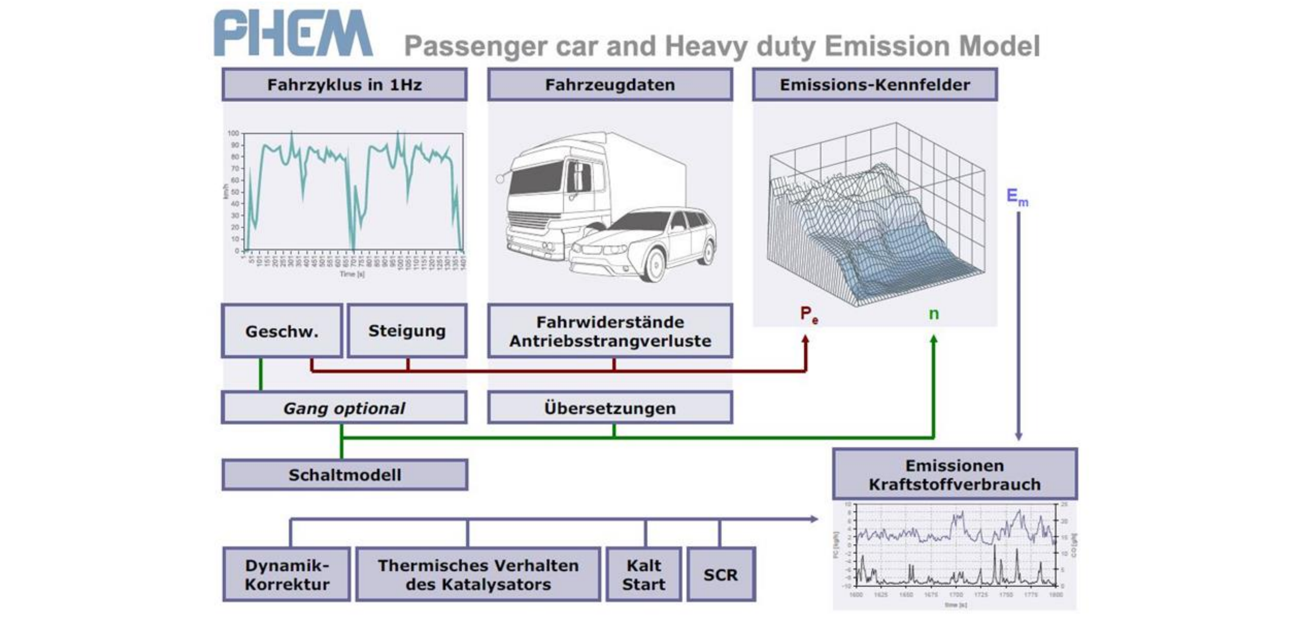

Figure 65: PHEM-simulation scheme (Hausberger et al. 2018)

Table 47: Characteristics of fuels used in PHEM simulation (Hausberger et al. 2018)

Type of fuel	Density	LHV	CO_2 emission factor	
	[kg/m³]	[MJ/kg]	[g/MJ]	[kg/kg]
Petrol	743.3	43.2	73.4	3.17
Petrol E5	745.8	42.3	73.3	3.10
Ethanol	794.0	26.8	71.4	1.91
Diesel	832.0	43.1	73.2	3.16
Diesel B7	836.1	42.7	73.4	3.13
FAME	890.0	37.2	76.2	2.83
HVO	780.0	44.0	70.8	3.12
CNG (EU mix piped NG)	0.780	46.6	56.1	2.60
Hydrogen	0.084	120	0	0

9.5.3 Vehicle Data in PHEM

PHEM needs data in the Vehicle-File (Figure 66 and Figure 67) on the vehicle and the propulsion system. The main data are:

- Vehicle mass and mass of loading [kg]
- Reduced mass of the wheels [kg]
- Diameter of the wheel [m]
- Driving resistance coefficient [-]
- Cross sectional area of the vehicle [m²]
- Rolling resistance coefficient [-]
- Nominal power of the internal combustion engine and electric engine [kW]
- Rated speed of the internal combustion engine and electric engine [RPM]
- Idle speed of the internal combustion engine [RPM]
- Inertia of motor and gearbox/transmission [kgm²]
- Ratio of gearbox/transmission [-]
- Power for auxiliary services [kW]

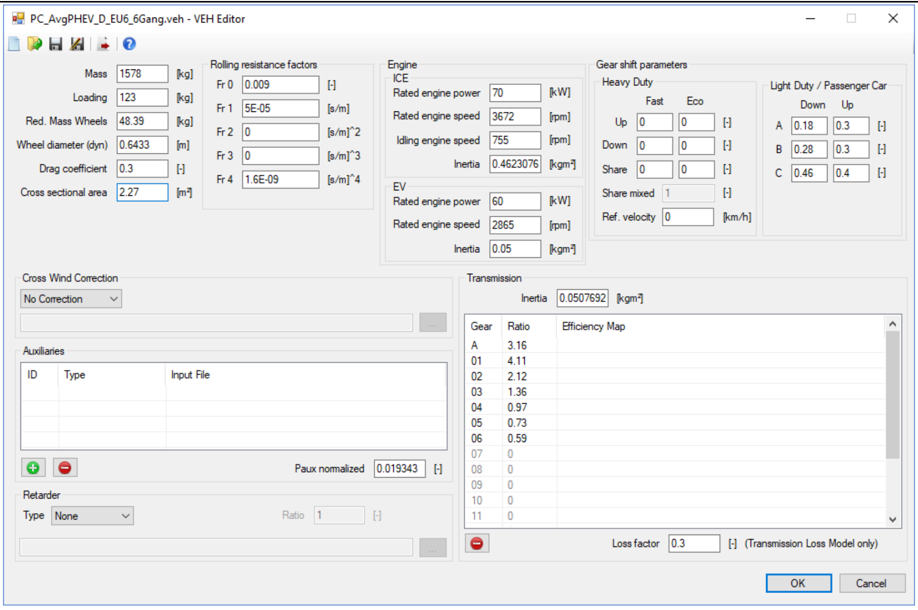

Figure 66: Vehicle data in PHEM (Hausberger et al. 2018)

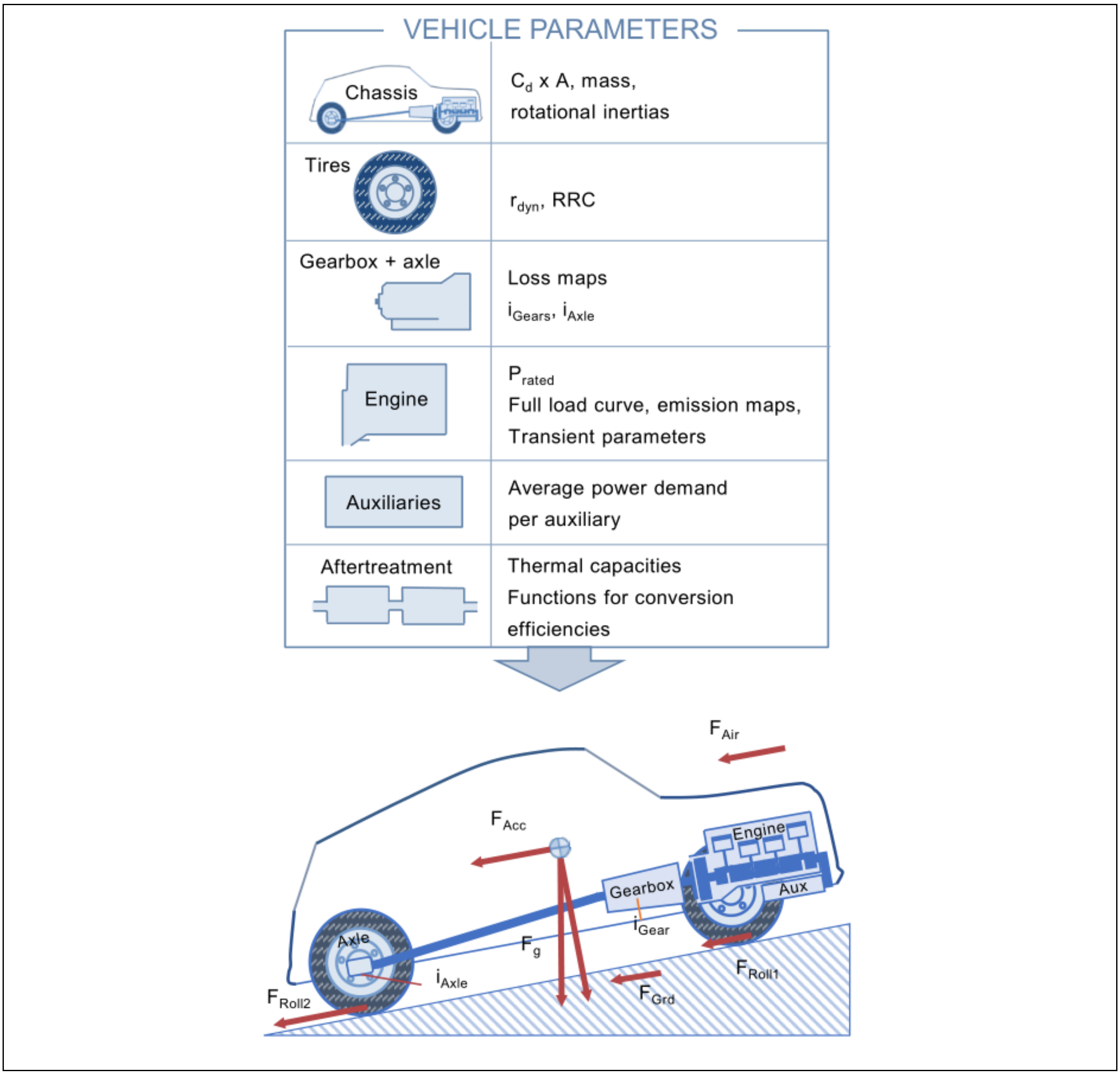

Figure 67: Summary of vehicle parameter (Hausberger et al. 2018)

With these data on the vehicle and the propulsion system the propulsion power per second for a given driving cycle is calculated. With the calculated power and engine speed the emission are determined in the emission map of the engine.

The estimated power for auxiliary services in the simulation is shown in *Table 48*. In the Handbook Emission Factors for Road Transport (HBEFA: http://www.hbefa.net/e/index.html) Study 3.3 the power is 1.204 kW for the auxiliary services of a conventional passenger vehicle. For the battery electric vehicles (BEV) and the Fuel Cell vehicles (FCV) in central Europe an additional power of 300 W was assumed, as the cabin heating is done by electricity. For the cooling of the cabin an equivalent power demand is estimated, which is already covered by the basic power demand of the auxiliary services of a conventional passenger vehicle.

For a PHEV, assuming a share of 50:50 for driving with ICE and e-engine, an additional demand for auxiliary services of 150 W was added.

Table 48: Estimation power for auxiliary services (Hausberger et al 2018)

Power of auxiliary services [kW]		**remark**
ICE	1.204	taken from HBEFA Studie 3.3
BEV & FCEV	1.504	plus 300 W for electr. heating and cooling(1)
PHEV	1.354	plus 150 W

(1) The energy demand for heating and cooling was calculated for a BEV based on a central European hourly temperature curve

9.5.4 Driving Cycle

For the simulation a Real World Cycle (RWC) was taken that corresponds mainly with the standard route for the measurement of the Real Driving Emissions (RDE) at the Institute of Combustion Engine and Thermodynamics at the Graz University of Technology. This RWC fulfills the requirements for the RDE compliant route and contains a mix of about 1/3 of urban, sub urban/overland and highway driving. The route is about 85 km long and has inclinations up to 10% to declinations up to 6 %. This cycle is mainly representative for the average vehicle use, for which the RWC cycle with speed and route gradient (inclination/declination) over time is shown in *Figure 68*.

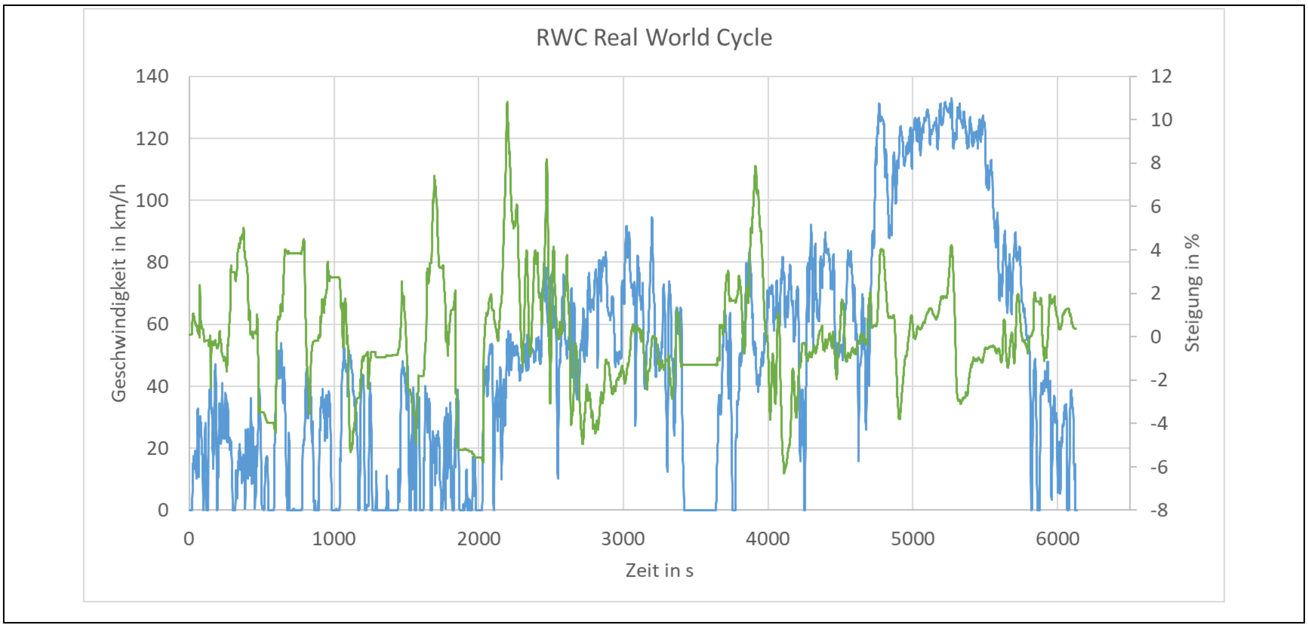

Figure 68: RWC cycle for the simulation

9.5.5 Emission Maps in PHEM

Based on the calculated power and engine speed the emissions are determined by using given emission maps. For the simulation in PHEM the average emission maps and full load profiles from the Handbook Emission Factors for Road Transport (HBEFA: http://www.hbefa.net/e/index.html) for passenger vehicles EURO 6 were used.

9.6 Vehicle Production

In this chapter the material and energy balance of the whole vehicle production is described by analysing the basic vehicle, the internal combustion engine, the electric engine, the battery, the fuel cell system and the hydrogen tank system.

9.6.1 Weight Estimation of Vehicles

Starting with an average middleclass vehicle (e.g. VW Golf 7) the mass of the vehicle was analyses and the shares for the following vehicle components were estimated (based on Hausberger et al. 2018):

- the cassis,
- the propulsion system,
- the after gas treatment,

- the tank and storage systems and
- the wheels with the rims.

Then an estimation of the material composition was done for these vehicle components.

First the mass of the basic vehicle is estimated, and based on that the single components of the different propulsion systems are added to get the mass of the different vehicles for the simulation in PHEM. In *Table 49* the estimation of the mass for the basic vehicle for the year 2018 is shown, which is finally about 876 kg.

Table 49: Estimation of the basic vehicle cassis mass (based on Hausberger et al. 2018)

Component	**kg**	**remark**
Passenger vehicle middle class with Otto engine	1,211	Average vehicle with Otto engine of HBEFA 3.3 (Handbuch für Emissionsfaktoren) study; DIN empty mass without additional equipment and 90% filled tank
Internal combustion engine	165	Assumption: Otto engine
After gas treatment system	15	Assumption: after gas treatment of Otto engine (3-way catalyst)
Fuel capacity	40	90% filled according to definition DIN-Mass, assumed tank volume 60 l, fuel data according to EUCAR
Fuel storage system	15	Assumption
wheels with the rims	85	Assumption
Cassis of basic vehicle 2018	876	

Based on the mass of the basic vehicle cassis the total mass for the different vehicle concepts are estimated. The following propulsion system are considered

- ICE – Internal combustion engine
- BEV – Battery electric vehicle
- HFC – Hydrogen fuel cell
- PHEV – Plug in Hybrid vehicle

The procedure of the mass estimation, which ensures a fair comparison between the different propulsion systems, is shown with the PHEV with diesel ICE as an example. The PHEV is built up with the components of the propulsion system shown in *Figure 69*. In contrast to an HEV the battery of a PHEV is larger and can be charged with grid electricity.

The propulsion system of the PHEV with a diesel ICE consists of the following components:

- Diesel ICE
- Electric engine
- High power battery
- Inverter
- DC converter

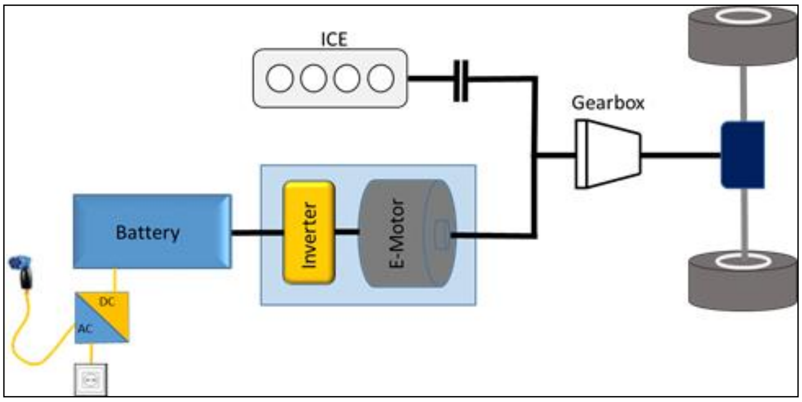

Figure 69: Scheme of the components of the propulsion system in a PHEV

In contrast to an ICE or HEV vehicle additionally also more cables and a charger for the battery are necessary. The estimation of the masses of the different components was done with the parameters and factors shown in *Table 50*.

The estimation of the mass of the electric engine for the different propulsion concepts was done based on an empiric formula of the University of Technology in Darmstadt. The correlation between mass of the electric engine is depending on the nominal power and torque, which is shown in *Figure 70*. For the mass calculation the formula for the permanently excited synchronous machine - PSM was used.

With these parameters the masses of the different components were estimated and the mass of the basic vehicle was added. So in total the mass of the whole PHEV vehicle was estimated with 1,578 kg for the simulation in PHEM in *Table 51*.

This estimation shown for the PHEV is also done for all the different propulsion and vehicle concepts to calculate the total mass for the simulation in PHEM. The main parameters for the estimation of the mass for the different components are shown in Table 52 and Table 53. The results of the estimated mass for the different components are shown in Table 54 and Table 55.

Table 50: Parameters and factors for the estimation of the masses of the different components of the PHEV (based on Hausberger et al. 2018)

Component	**data**	**Unit**	**Remarks/source**
Tank volume	40	[l]	Assumption
Battery voltage	314	[V]	Nominal voltage of high-capacity battery
Battery capacity	9.9	[kWh]	Based on Ricardo-Study[1] and typical for current PHEVs
Battery energy density	80	[Wh/kg]	Source: EUCAR
Torque electric engine	200	[Nm]	Typical current value
Power electric engine	60	[kW]	Typical current value
Power ICE	70	[kW]	Typical current value for a new middle class PHEV

[1]… Study to estimate the CO_2-reduction due to future technologies (2014)

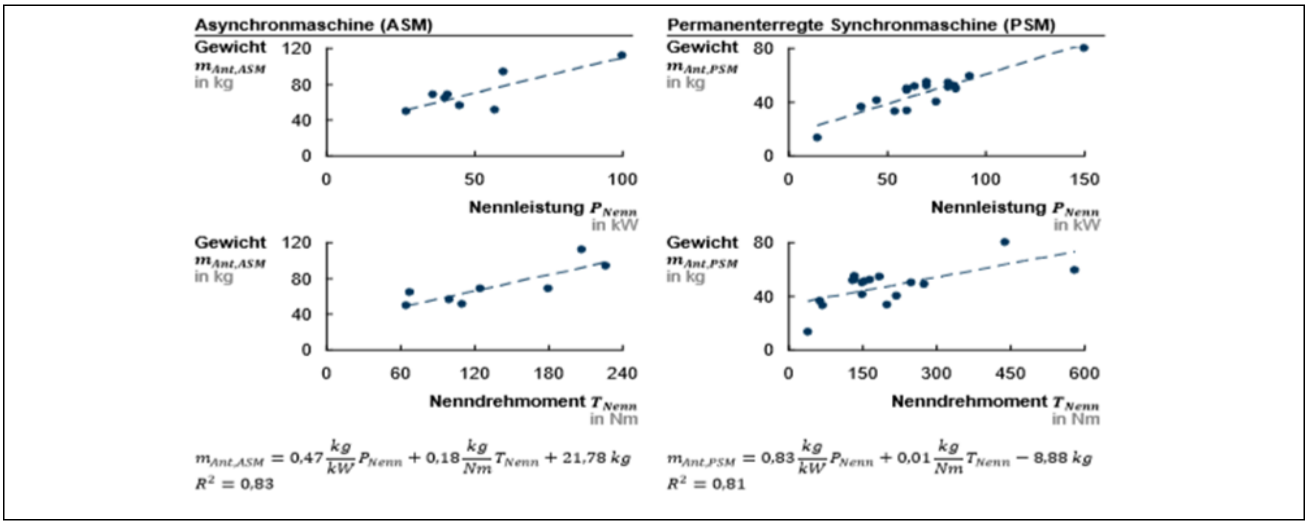

Figure 70: Modell for the estimation of the mass of an electric engine (asynchronous machine - ASM and permanently excited synchronous machine - PSM) in relation to power and torque

Table 51: Estimation of the mass of a PHEV (based on Hausberger et al. 2018)

Component	kg	remarks
Basic vehicle cassis	876	See Table 49
Wheels with the rims	85	Assumption
Electric engine	43	Calculation based on empiric formula of power and torque of an electric engine (see Figure 70)
DC converter	5	Assumption
Inverter	7	Assumption
Additional cabling	56	Assumption: 20 m additional copper cables with 20 mm diameter
Charger	12	Assumption
High capacity battery	124	Calculated with capacity and energy density of battery
After gas treatment	45	For a diesel ICE (e.g. DOC, DPF, SCR)
Diesel ICE	215	Assumption
Tank filling (liquid)	30	Filled to 90%
Fuel tank	15	Assumption for liquid fuel
Additional equipment	65	Assumption
Total mass of PHEV	1,578	Calculated

Table 52: Estimation of parameter for different components (FCEV, HEV, BEV) (Hausberger et al. 2018)

Komp./Parameter	Größe	für Fzg.-Technologie	Einheit
Spez. Gewicht Kraftstoffspeicher / Tank	*0.65*	FCEV	*kW/kg*
Spez. Gewicht Kraftstoffspeicher / Tank	*0.6*		*kW/l*
Tankvolumen	*140*		*l*
Batteriekapazität	*1.25*		*kWh*
Batteriespannung (Nominalspannung)	*320*		*V*
Energiedichte Batterie	*80*		*Wh/kg*
Energiedichte Brennstoffzelle	*650*		*Wh/kg*
Spannungswandler	*5*		*kg*
Umrichter	*7.5*		
Drehmoment E-Motor	*300*		*Nm*
Leistunge E-Motor	*90*		*kW*
Nenndrehzahl E-Motor	*2865*		*U/min*
Leistung Brennstoffzelle	*90*		*kW*
Tankvolumen	*40*	HEV	*l*
Batteriekapazität	*1.5*		*kWh*
Energiedichte Batterie	*50*		*Wh/kg*
Batteriespannung (Nominalspannung)	*250*		*V*
Spannungswandler	*5*		*kg*
Umrichter	*7.5*		*kg*
Drehmoment E-Motor	*200*		*Nm*
Leistung E-Motor	*25*		*kW*
Nenndrehzahl E-Motor	*1194*		*U/min*
Leistung ICE	*70*		*kW*
Batteriekapazität	*35*	BEV	*kWh*
Batteriespannung (Nominalspannung)	*350*		*V*
Energiedichte Batterie	*110*		*Wh/kg*
Umrichter	*10*		*kg*
Spannungswandler	*5*		*kg*
Ladegerät	*12*		*kg*
Drehmoment E-Motor	*300*		*Nm*
Nenndrehzahl E-Motor	*2865*		*U/min*
Leistung E-Motor	*90*		*kW*

Table 53: Estimation of parameter for different components (PHEV, CNG, Otto and diesel ICE) (Hausberger et al. 2018)

Tankvolumen	*40*	PHEV	*l*
Batteriespannung (Nominalspannung)	*314*		*V*
Batteriekapazität	*9.9*		*kWh*
Energiedichte Batterie	*80*		*Wh/kg*
Umrichter	*7.5*		*kg*
Spannungswandler	*5*		*kg*
Ladegerät	*12*		*kg*
Drehmoment E-Motor	*200*		*Nm*
Leistung E-Motor	*60*		*kW*
Nenndrehzahl E-Motor	*2865*		*U/min*
Leistung ICE	*70*		*kW*
Tankvolumen Flüssig	*50*	CNG	*l*
Tankvolumen Gas	*15*		*kg*
Spez. Gewicht Kraftstoffspeicher / Tank Gas	*0.75*		*kg/l*
Batteriekapazität	*0.8*		*kWh*
Tankvolumen	*60*	Otto / Diesel	*l*
Energiedichte Batterie	*40*		*Wh/kg*
Batteriekapazität	*0.6*		*kWh*
ICE (Internal Combustion Engine inkl. Getriebe)	*165*	Otto	*kg*
	215	Diesel	
Abgasnachbehandlungssystem	*15*	Otto	
	45	Diesel	
Kraftstoffspeicher / Tank	*15*	Otto & Diesel	
Masse 4 Räder + Felgen	*85*	alle	
Zusätzliche Verkabelung Länge	20	BEV, PHEV, FCEV, HEV	*m*
Kabeldurchmesser	20		*mm*
Dichte Kupfer	8.94		*kg/dm³*

<u>Table 54:</u> Estimated masses of vehicle components (BEV, HEV and FCHV) (Hausberger et al. 2018)

Komponente / Parameter	**Gewicht in kg**	**Fzg. Technologie**
Karosserie Basisfahrzeug	*876*	FCEV
Kraftstoffspeicher / Tank	*138*	
Räder + Felgen	*85*	
Tankinhalt H_2 (halb voll)	*2.7*	
zusätzliche Verkabelung	*56*	
Spannungswandler	*5*	
Umrichter	*7.5*	
Batterie	*16*	
Brennstoffzelle	*138*	
E-Motor	*69*	
Masse Basisfahrzeug	***1394***	
Karosserie Basisfahrzeug	*876*	HEV_G
Kraftstoffspeicher / Tank	*15*	
Räder + Felgen	*85*	
ICE (Otto)	*165*	
E-Motor	*14*	
Spannungswandler	*5*	
Umrichter	*7.5*	
zusätzliche Verkabelung	*56*	
Batterie	*30*	
Abgasnachbehandlung (Otto)	*15*	
Tankinhalt (Otto, halb voll)	*15*	
Masse Basisfahrzeug	***1283***	
Karosserie Basisfahrzeug	*876*	BEV
Räder + Felgen	*85*	
E-Motor	*69*	
Spannungswandler	*5*	
Umrichter	*10*	
zusätzliche Verkabelung	*56*	
Ladegerät	*12*	
Batterie	*318*	
Masse Basisfahrzeug	**1431**	

Table 55: Estimated masses of vehicle components (PHEV, CNG, Otto and diesel ICE) (Hausberger et al. 2018)

Karosserie Basisfahrzeug	*876*	PHEV_G
Räder + Felgen	*85*	
E-Motor	*43*	
Spannungswandler	*5*	
Umrichter	*7.5*	
zusätzliche Verkabelung	*56*	
Ladegerät	*12*	
Batterie	*124*	
Abgasnachbehandlung (Otto)	*15*	
ICE (Otto)	*165*	
Tankinhalt (Otto, halb voll)	*15*	
Kraftstoffspeicher / Tank	*15*	
Masse Basisfahrzeug	**1418**	
Karosserie Basisfahrzeug	*876*	CNG
Räder + Felgen	*85*	
ICE (Otto)	*165*	
Kraftstoffspeicher / Tank CH_4	*11*	
Krafstoffpeicher / Tank Otto	*15*	
Tankinhalt (Otto, halb voll)	*19*	
Tankinhalt (CH_4 halb voll)	*7.5*	
Abgasnachbehandlung (Otto)	*15*	
Batterie	*15*	
Masse Basisfahrzeug	**1208**	
Karosserie Basisfahrzeug	*876*	Otto
Räder + Felgen	*85*	
Batterie	*15*	
Kraftstoffspeicher / Tank	*15*	
Tankinhalt (Otto, halb voll)	*22*	
Abgasnachbehandlung (Otto)	*15*	
ICE (Otto)	*165*	
Masse Basisfahrzeug	**1193**	
Karosserie Basisfahrzeug	*876*	Diesel
Räder + Felgen	*85*	
Batterie	*15*	
Kraftstoffspeicher / Tank	*15*	
Tankinhalt (Diesel, halb voll)	*25*	
Abgasnachbehandlung (Diesel)	*45*	
ICE (Diesel)	*215*	
Masse Basisfahrzeug	**1276**	

The results of the estimation of the whole mass of the different vehicles are shown in Table 56. As loading mass it was assumed that 1.3 persons are passenger vehicle occupants, with a mass of 75 kg each and additional luggage with 25 kg. The total mass for the simulation in PHEM is the mass of the vehicle plus the loading mass. The total propulsion power of the ICE, BEV and FCEV is 90 kW each. For PHEV are higher power was assumed as the vehicle can be driven either by ICE or by electric engine. The driving range for BEV was assumed minimum 300 km.

<u>Table 56:</u> Power and mass of the different vehicle and propulsion systems (based on Hausberger et al. 2018)

Vehicle propulsion system	Vehicle mass for PHEM [kg]	Nominal power ICE [kW]	Nominal power electric engine/fuel cell [kW]
Diesel ICE	1,361	90	-
Petrol ICE	1,276	90	-
CNG ICE	1,301	90	-
Diesel HYB	1,443	70	25
Petrol HYB	1,360	70	25
Diesel PHEV	1,578	70	60
Petrol PHEV	1,495	70	60
FCEV	1,461	-	90
BEV	1,496	-	90

9.6.2 Material Mix of Vehicles

The material mix was analysed and estimated based on the data of the current VW Golf 7. Additionally the following sources were used:

- Friedrich H. (2017). Zur Zukunft der Mobilität: Randbedingungen, Fahrzeugkonzepte, Funktionen und Technologien. Vortrag bei “ Nachhaltigkeit und Mobilität in der gebauten Umwelt.” 13. Juli 2017, Rottweil, Deutschland.
- Thaden G. et al. (2017). Automotive metal components for car bodies and chassis. Global market study. Roland Berger, Automotive Competence Center. London, UK.
- Online article. (2018). Aluminum wrestles with steel over electric vehicle market”. Veröffentlicht 27. März 2018. https://www.reuters.com/article/us-autos-metals-electric-vehicles-analys/aluminum-wrestles-with-steel-over-electric-vehicle-market-idUSKBN1H31M7

- Online Artikel (2012). Benchmarking Golf VI. Veröffentlicht 2012. www.plastics.gl/automotive/benchmarking-golf-vii/
- https://portal.a2mac1.com (Automotive Benchmarking)

The main result of literature search was that no significant change in the material mix is expected in the segment of the current VW Golf. The issues of lightweight, which is currently becoming relevant due to the additional load of the battery in BEV, will be realized in future – according to the current expert discussion – with a material mix of high and ultra-high-tensile steel with shares of aluminium and constructive improvements (see Figure 71). Higher shares of aluminium and expensive materials like magnesium and carbon fibre composites will become more relevant for upper vehicle classes.

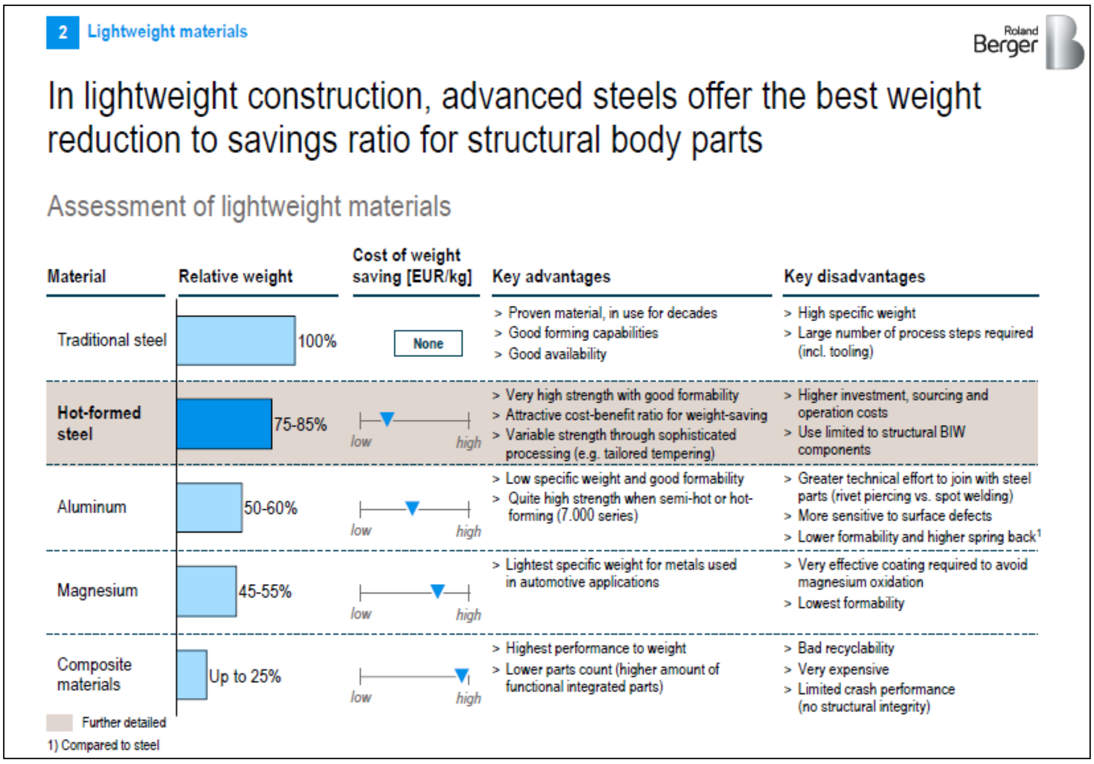

Figure 71: Advantages and disadvantages of different lightweight materials

9.6.3 Energy Demand for Vehicle Manufacturing

The energy demand for the basic vehicle manufacturing in car factory is estimated based on the VW Sustainability report (https://www.volkswagenag.com/en/sustainability/reporting.html) the following:

- Electricity: 1,060 kWh/vehicle
- Heat: 587 kWh/vehicle
- Natural gas: 421 kWh/vehicle

9.6.4 Fuel Cell and Hydrogen Tank

For the environmental assessment of the fuel cell for hydrogen the following references were used:

- Garche S. (2018). Wasserstoff & Brennstoffzelle – Quantensprung im Umwelt- und Klimaschutz? (Hydrogen and Fuel Cell - Quantum Leap Fort he Environment and Climate Protection?), presentation. 8.6.2018. Velden, Austria.
- Hartmann U. (2017). Sustainability management and environment @ Daimler. Vortrag, SRI Conference. 7. Februar 2017. Frankfurt, Deutschland.
- Tokieda J. (2015). The Mirai Life Cycle Assessment Report. Toyota Motor Company.
- Toyota. (2018). Toyota Mirai. Brochure. Toyota Motor Corporation. Japan.
- Notter D. et al. (2015). Life cycle assessment of PEM FC applications. Energy and Environmental Science. Issue 7, 2015.
- Evangelisti S., Tagliaferri C. Lettieri P. (2017). Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. Journal of Cleaner Production, Vol 142, Part 4. Jan 2017.
- Mitzel J. et al. (2017). Wasserstoff und Brennstoffzellen. (Hydrogen and Fuel Cell), Article in BWK Bd. 69 (2017) Nr.5, p.124-134.
- Simons A., Bauer C. (2015). A life-cycle perspective on automotive fuel cells. Applied Energy, 157. March 2015.

In *Figure 72* the main process for the manufacturing of a PEM-fuel cell system for a passenger vehicle are shown.

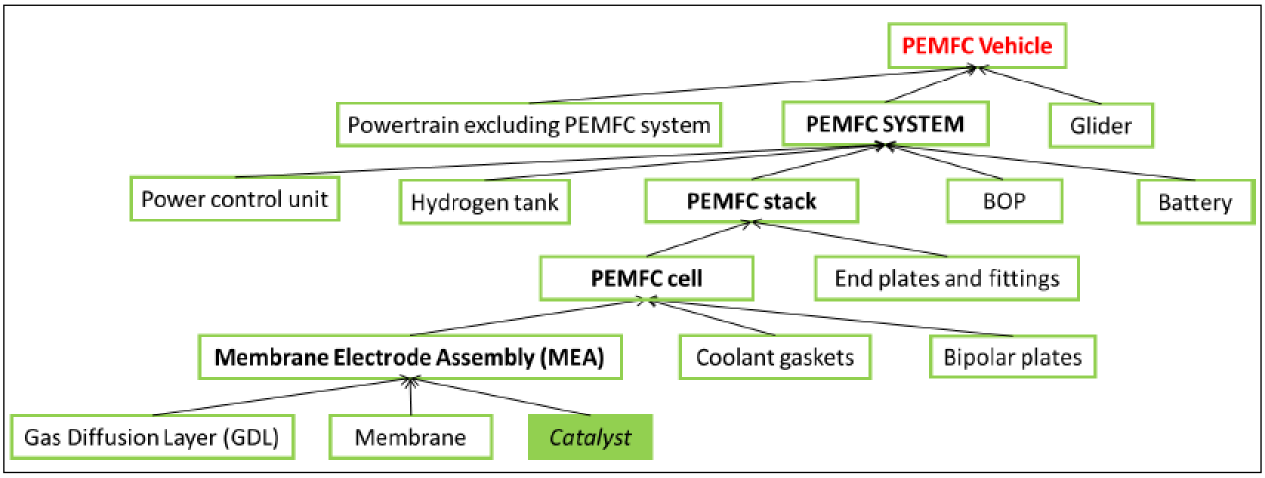

Figure 72: Scheme of the manufacturing processes of a PEM fuel cell (Evangelisti 2017)

The total mass of a 90 kW PEM-fuel cell system is estimated by Graz University of Technology with about 138 kg (based on Hausberger et al. 2018). For the 90 kW fuel cell stack 14 g of platinum load are assumed (Evangelisti 2017). The fuel cell of the Mercedes GLC F-Cell has 20 g platinum for 150 kW (Hartmann 2017). In the Toyota Mirai there are 30 g platinum for 90 kW. For the current state of technology the platinum load is estimated between 10 – 12 g for a 100 kW fuel cell stack (Garche 2018).

For the current model of the Toyota Mirai the mass of the fuel cell stack incl. casing is estimated with 56 kg (Toyota 2018). The lower mass is due to the use of titanium instead of steel for the separators (bipolar plates) and the aluminum casing instead of steel. These measures let to a mass reduction of about 42% compared to the previous model[6]. Additionally the mass balance of Toyota does not include additional power units like fans, pumps and control modules.

The share of the total mass of a fuel cell system is shown in Figure 73. About 2/3 of the mass are the separators (Bipolar Flow Plates) of the cells made of steel. The shares of the total GHG emissions of the fuel cell system of 835 kg $CO_{2\text{-eq}}$ are shown in *Figure 74*. About 50% are caused by the platinum based catalyst.

The mass of the hydrogen fuel tank made from carbon fibers is estimated with 138 kg (based on Hausberger et al. 2018).

[6] https://www.greencarcongress.com/2015/04/20150429-mirai.html

The energy demand for the manufacturing of the fuel cell is about 11 kWh electricity per kW of fuel cell power and 4.5 kWh for the hydrogen tank (Evangelisti 2017).

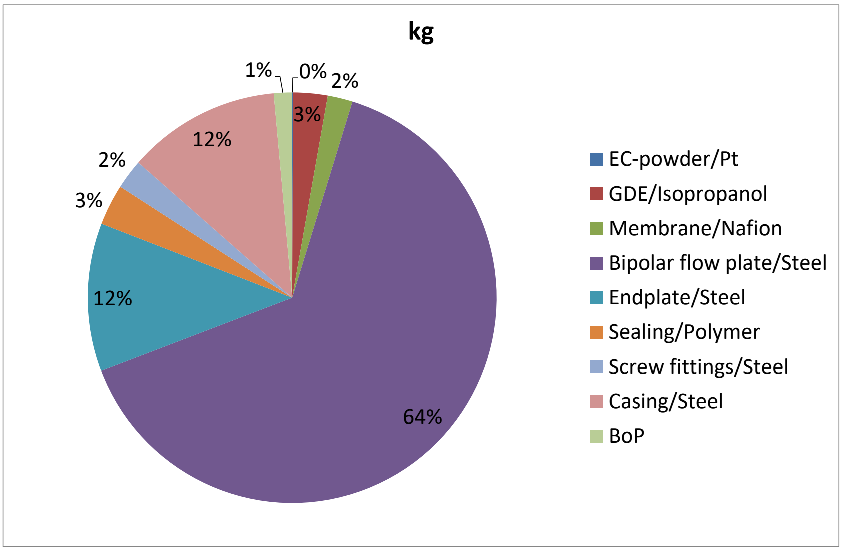

Figure 73: Shares of mass of PEM-fuel cell system (Evangelisti 2017)

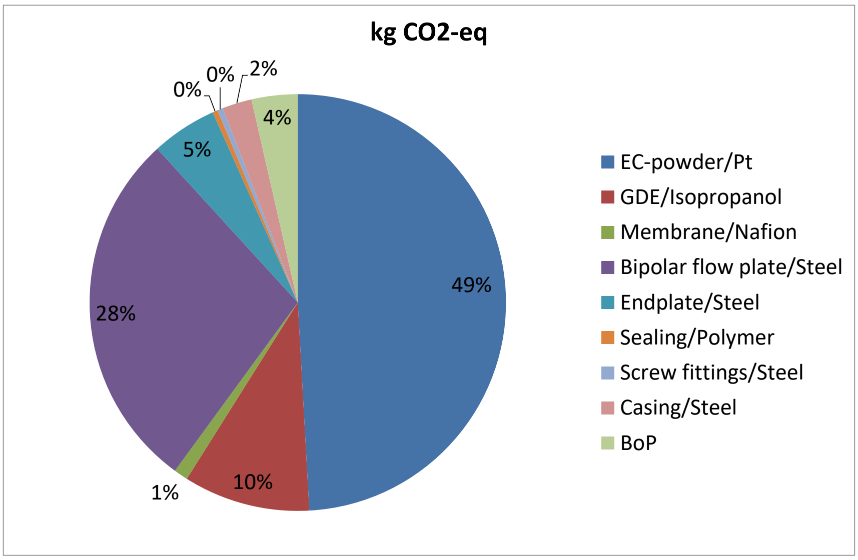

Figure 74: Share of GHG emissions of manufacturing of a PEM-fuel cell system

9.7 Charging Infrastructure for Electric Vehicles

The main issues of the analysis of the charging infrastructure were the energy loses of current fast DC charging with 50 kW according to state of technology.

In Figure 75 an overview of currently used charging systems with different charging power is shown.

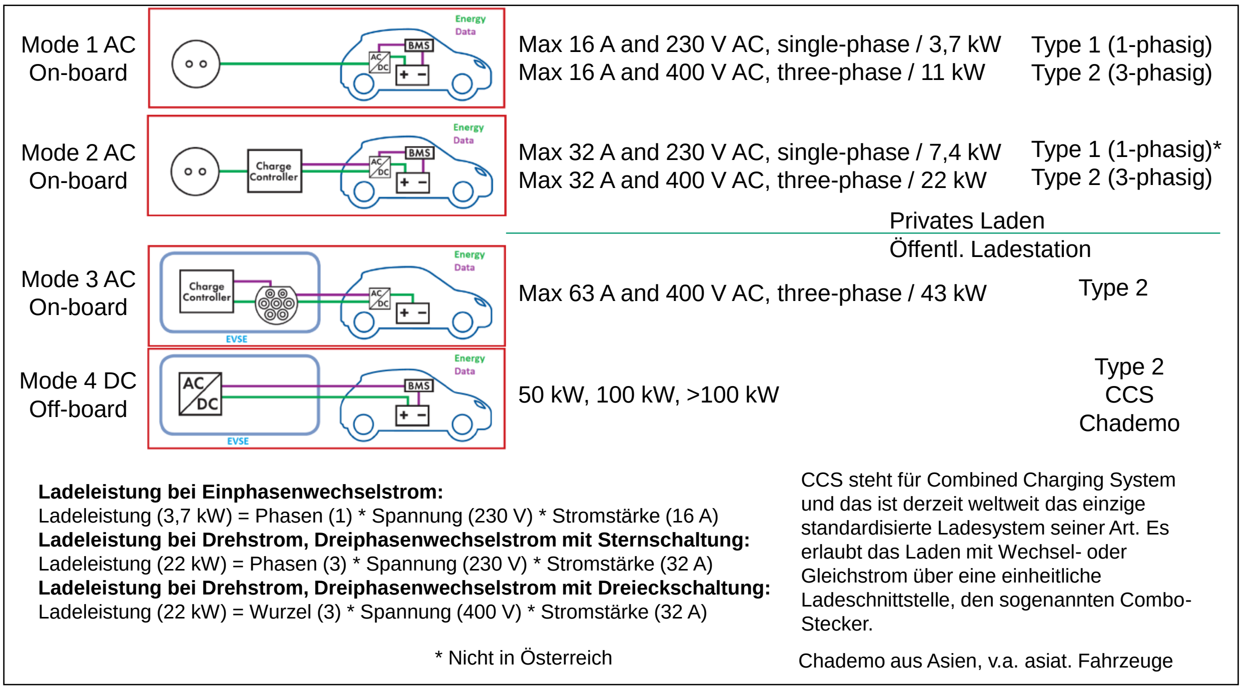

Figure 75: Charging losses and plug systems of on-board and off-board charging systems

A comprehensive measurement program of charging losses is currently undertaken by the JRC [7]. The preliminary results of the monitoring of a 50 kW DC charging station are (*Figure 76*):

- The losses of currently available DC charging stations (50 kW peak power) are between 8 to 11%.
- The main influence on the losses is the actual used power in relation to the nominal power. In the case of actual charging with only 10% of the nominal power the energy losses can be up to 50%.
- The low actual charging power might have different reasons: low outside temperature, requirements of the charging control system of the vehicle, e.g. limitation of fast charging cycles due to the lifetime of the battery, charging power of the battery type.

[7] Scholz H. (2017). Stand-by power consumption, efficiency under operational load and EMC of DC chargers for EVs. Presentation in expert Workshop on energy efficiency of EVSE, Wien 2017.

- Based on the ongoing deployment of fast charging stations with more than 100 kW (e.g. Ionity-HPC-Station with up to 350 kW[8]) the charging losses are expected to further increase with current state of technology. [9]

CCS BMW i3:
Efficiency measurements of charging columns

Chargers	25°C		40°C		-20°C	
	Efficiency	Power	Efficiency	Power	Efficiency	Power
A	90.38%	40.3kW	90.35%	39.15kW	Out of order	
B	89.84%	44.47kW	89.87%	42.2kW	64.51%	6.52kW
C	Not tested: column out of order					
D	90.56%	46.40kW	90.89%	45.06kW	78.84%	7.55kW

Values obtained from the median of the stable charging conditions.

European Commission

CHAdeMO NISSAN LEAF:
Efficiency measurements of charging columns

Chargers	25°C		40°C		-15°C		-25°C	
	Efficiency...	...@ Power	Efficiency...	...@ Power	Efficiency...	...@ Power	Efficiency...	...@ Power
A	90.8%	40.37kW	91.18%	40.2kW	36.26%	4.18kW	Out of order	Out of order
B	91.47%	48.24kW	89.13%	47.35kW	Not tested	Not tested	56.65%	4.1kW
C	91.76%	37.61kW	92.4%	37.36kW	89.5%	21.21kW	Out of order	Out of order
D	92%	47.09kW	91.21%	45.9kW	Not tested	Not tested	72.83%	4.42kW
E	92.1%	45.77kW	to be tested		to be tested		to be tested	
F	to be tested		to be tested		84.15%	22.95kW	51.5%	5.15kW
G	90.48%	45.45kW	to be tested		Out of order	Out of order	Out of order	Out of order

Values obtained from the median of the maximum stable charging conditions.

European Commission

Figure 76: Efficiencies of 50 kW DC-charging stations [14]

For comparison the company Smatrics[10] concludes about 17% charging losses of their AC (22kW) / DC (50 kW) charging stations.

[8] https://www.ots.at/presseaussendung/OTS_20181018_OTS0032/omv-und-ionity-eroeffnen-die-ersten-350-kw-high-power-ladestationen-in-oesterreich

[9] Apostolaki-Iosifidou E. et al. (2017). Measurement of power loss during electric vehicle charging and discharging. http://dx.doi.org/10.1016/j.energy.2017.03.015

[10] Smatrics (2017). Presentation in expert Workshop on energy efficiency of EVSE, Wien 2017.

10. Annex II: Comparison of Greenhouse Gas Emission of Electricity

10.1 Introduction

In this annex the results of the greenhouse gas emissions from the current (2018) electricity mix in Austria, German and Switzerland are compared to greenhouse gas emissions that are currently used in these countries, which are (partly) published from the Environmental agencies (Umweltbundesamt in Austria and Germany) and the Bundesamt für Energie BFE in Switzerland ("official data"). For this comparison these organisations were directly contacted to get the necessary background information on the calculation method and data used for the greenhouse gas emissions of the electricity mix. In general, it was difficult to get the comprehensive and complete information on the calculation method and data use.

The available information was used to compare the greenhouse gas emissions with the calculation used in the LCA tool, which is described in the main report. For the comparison and the understanding of the possible difference the following aspects were considered:

- Listing the references
- Reference year of the electricity mix: 2019
- Methodological approach: LCA
- Considered greenhouse gases: CO_2, CH_4 and N_2O
- Share of energy carriers in the national electricity production mix (see Table 57 from IEA statistics)
- Considering import and exports of electricity: net import as difference of imported and exported electricity
- Electricity grid losses: 5,5 %/ 100 km
- Allocation of coproduced heat for district heat in thermal power plants: energy allocation based on IEA energy statistic for district heat and electricity production in thermal CHP plants
- Greenhouse gas emissions of national electricity production mix: see Table 57 based on generic types and default data of different power plants

- Greenhouse gas emissions from imported electricity mix: additional electricity of power plants made using fossil and nuclear energy in the European mix 2018: 590 g CO_2-eq/kWh (EU 2018)

- Greenhouse gas emissions from consumed electricity mix: see Table 57

- Summary of main difference

10.2 Comparison

10.2.1 Summary of comparison for all countries

In Table 57 the summary of the parameters and the comparison for the different aspects are given, which are described in the following chapter for each country in detail. This comparison was also send to the colleagues from AT (Werner Pölz, UBA Wien), DE (Petra Icha, UBA DE), and CH (Stephan Walter, BFE, Philippe Stolz, treeze) and the received comments were integrated.

Table 57: Summary of parameters and comparison

	AT		DE		CH	
	LCA tool	**UBA AT**	**LCA tool**	**UBA DE**	**LCA tool**	**treeze/BFE**
reference year	2018	2017	2018	2015	2018	2014
methodology	LCA	LCA	LCA	LCA	LCA	LCA
GHG gases	CO2, CH4, N2O	CO2, CH4, N2O (if CO2eq from GEMIS: as in DE)	CO2, CH4, N2O	CO2, CH4, N2O, Perfluorethan, Perfluormethan	CO2, CH4, N2O	CO2, CH4, N2O, SF6
national electricity production						
coal	5.3%	5.5%	35.7%	42.3%	0%	0%
oil	1.0%	1.2%	0.9%	0.8%	0.1%	0.04%
natural gas	14.8%	16.2%	12.6%	11.5%	1.4%	0.8%
nuclear	0%	0%	11.6%	14.2%	36.1%	37.6%
biomass	7.2%	7.5%	8.3%	6.6%	2.4%	2.4%
hydro	60.7%	57.6%	3.6%	3.0%	55.3%	56.0%
wind	8.2%	8.6%	18.3%	13.6%	0.2%	0.1%
PV	1.8%	1.9%	7.5%	6.0%	2.8%	1.2%
waste	1.0%	1.6%	1.1%	1.8%	1.7%	1.9%
other			0.3%	0.2%		
	100%	100%	100%	100%	100%	100%
methodology in the consideration of electricity market	fossil & nuclear share of the European mix 2018	countries of origin (56% DE, 39% CZ, e-control2017) [1]	fossil & nuclear share of the European mix 2018	electricity trade balance Tab. 1 [4]	fossil & nuclear share of the European mix 2018	considering import and export according to electricity origin certificate
electricity market	net import (12%)	28% absolute, 15.6% net	no import because export higher than import	total electricity market (net export)	no import because export higher than import	total electricity market (net import)
consideration of coproducted heat in CHP plants	yes, energy allocation factor for electricity: 57%	no, info in mail or reports	yes, energy allocation factor for electricity: 82%	yes, applying the Finisch method [3]	no (not necessary because the share of calorific plants is very small)	no (not necessary because the share of calorific plants is very small)
net losses	5.5% (per 100km and abs.)	6% / 100km [2]	5.5% (per 100km and abs.)	5-6% [5]	5.5% (per 100km and abs.)	7% (table 2.1) [7]
share of import	12% (net)	28% (abs) [1], 15.6% (net) [2]	0% (because import higher than export)	8% net export, p. 15 [4]	0% (because import higher than export)	30% [7]
greenhouse gas emissions of the the different electricity mix [gCO2eq/kWh]						
inland production mix	103 (169 without alloc.)	180 [2]	415 (500 without alloc.)	547 [6]	55	29.8 [7]
import mix	590	616 [2]	590	no info found	590	457
mix at the charging point	**162**	**248** [2]	**415**	**580** [3+5]	**55**	**181.5** [7]
References	LCA tool calculations	UBA AT [1] Pölz, tel. & mails (16.7.)	LCA tool calculations	UBA DE [3, 4] mails Gärtner & Niedermaier	LCA tool calculations	treeze [7] mails Walter (BFE) and Stolz (treeze)

1) UBA AT Report "Treibhausgasemissionen von Strom, Empfehlungen zur Öko-Bilanzierung", Kranzl Sabine, 2018
2) Telefon call and mail with Pölz at 16.7.
3) UBA DE report "Emissionsbilanz erneuerbarer Energieträger", 23/2018, M. Memmler, T. Lauf
4) UBA DE report "Entwicklung der spez. Kohlendioxidemissionen des DE-Strommixes 1990-2018", Petra Icha, 2019
5) from Niedermaier's mail.
6) GEMIS IINAS 2016
7) treeze report "Umweltbilanz Strommix Schweiz 2014 v3.0" (Messmer, Frischknecht)

10.2.2 Austria

For the comparison and the understanding of the possible difference the following aspects are described:

- Listing the references:
  - Personal communication with Umweltbundesamt
  - On-line CO_2 -Rechner des Umweltbundesamtes (http://www5.umweltbundesamt.at/emas/co2mon/co2mon.htmlreports)
  - UBA Wien Report „Treibhausgasemissionen von Strom, Empfehlungen zur Öko-Bilanzierung", Kranzl Sabine, 2018
- Reference year of the electricity mix: 2017
- Methodological approach: LCA
- Considered greenhouse gases: CO_2, CH_4 and N_2O
- Share of energy carriers in the national electricity production mix: see Table 57 quite similar in 2017 and 2018
- Considering import and exports of electricity: the annual net difference of imported and exported electricity is used, so 15.6% of electricity is imported
- Electricity grid losses: 6% per 100 km
- Allocation of coproduced heat for district heat in thermal power plants: Finish method and emission inventories are applied, but not reported in detail. In the LCA tool 43% of the GHG emissions are allocated to the coproduced heat.
- Greenhouse gas emissions of national electricity production mix 2017: 180 g CO_2-eq/kWh
- Greenhouse gas emissions from imported electricity mix: 616 g CO_2-eq/kWh mainly from Germany and Check Republic

- Greenhouse gas emissions from consumed electricity mix: 248 g CO_2-eq/kWh but not well reported in the on-line CO_2-Rechner des Umweltbundesamtes (additional information from mail of Werner Pölz, UBA)

- Comparison: the difference between 162 g CO_2-eq/kWh and 248 g CO_2-eq/kWh is due to
    - Methodological consideration of coproduced heat
    - Differences in data for power plants e.g. efficiencies

10.2.3 Germany

For the comparison and the understanding of the possible difference the following aspects are described:

- Listing the references:
    - UBA DE report „Emissionsbilanz erneuerbarer Energieträger, 23/2018“, M. Memmler, T. Lauf
    - UBA DE report „Entwicklung der spez. Kohlendioxidemissionen des DE-Strommixes“ 1990-2018, Petra Icha, 10/2019
    - Personal communication with Umweltbundesamt
    - Personal communication with ADAC

- Reference year of the electricity mix: 2015

- Methodological approach: LCA

- Considered greenhouse gases: CO_2, CH_4 and N_2O, possible that the CO_2eq emissions were directly taken from GEMIS, which also includes perfluorethane and perfluormethane

- Share of energy carriers in the national electricity production mix: see Table 57, since 2015 the share of coal power decreased and of wind power increased

- Considering imports and exports of electricity: the annual net difference of imported and exported electricity is used, so 8% of electricity is exported mainly surplus wind and PV electricity

- Electricity grid losses: 5 - 6% per 100 km
- Allocation of coproduced heat for district heat in thermal power plants: not documented in detail, but Finish method might have been applied. Based on IEA statistic in the LCA tool 18% of the GHG emissions are allocated to the coproduced heat
- Greenhouse gas emissions of national electricity production mix 2015: 547 g CO_2-eq/kWh, (if in LCA tool no allocation for coproduced heat is applied:500 g CO_2-eq/kWh)
- Greenhouse gas emissions from imported electricity mix: not relevant as net balance of electricity shows export
- Greenhouse gas emissions from consumed electricity mix: 580 g CO_2-eq/kWh
- Comparison: the difference between 415 g CO_2-eq/kWh and 580 g CO_2-eq/kWh is due to
    - Different national electricity production in 2015 compared to 2018, e.g. lower share of coal and higher share of wind in 2018
    - Consideration of imports and exports not documented
    - Unclear methodological consideration of coproduced heat
    - Differences in data for power plants

10.2.4 Switzerland

For the comparison and the understanding of the possible difference the following aspects are described:

- Listing the references:
    - the treeze report „Umweltbilanz Strommix Schweiz 2014 v3.0“ (Messmer et al. 2014)
    - Personal communication with BFE and treeze
- Reference year of the electricity mix: 2014
- Methodological approach: LCA
- Considered greenhouse gases: CO_2, CH_4, N_2O, and SF_6, but influence of SF_6 very low

- Share of energy carriers in the national electricity production mix: see Table 57 quite similar in 2014 and 2018
- Considering import and exports of electricity: imports and export according to the electricity origin certifications: 30% in 2014 and no import in 2018 based on IEA statistics
- Electricity grid losses: 7% total
- Allocation of coproduced heat for district heat in thermal power plants: not relevant as nearly no district heat from CHP plants
- Greenhouse gas emissions of national electricity production mix 2014: 30 g CO_2-Äq/kWh
- Greenhouse gas emissions from imported electricity mix: 457 g CO_2-eq/kWh
- Greenhouse gas emissions from consumed electricity mix: 182 g CO_2-eq/kWh
- Comparison: the difference between 55 g CO_2-eq/kWh and 182 g CO_2-eq/kWh is due to
  - No import was considered in the LCA tool due to the IEA data source for 2018, where the export in the year 2018 were higher than the import. treeze considering imports and exports according to the electricity origin certificates of 30% in 2014
  - Differences in data for power plants: 55 g CO_2-eq compared to 30 g CO_2-eq/kWh (especially the emissions from the nuclear plants are in treeze report significant lower than considered in the LCA tool)

In the Figure 77, Figure 78 and Figure 79 the comparison of the cumulated greenhouse gas emissions of the PHEV and BEV transportation systems for the three countries Austria, Germany and Switzerland are shown using the different GHG emissions from the tool and the “official data “ described above.

In Figure 80, Figure 81 and Figure 82 the comparison of the estimated GHG emissions per kilometre using the different GHG emission of the electricity mixes are shown.

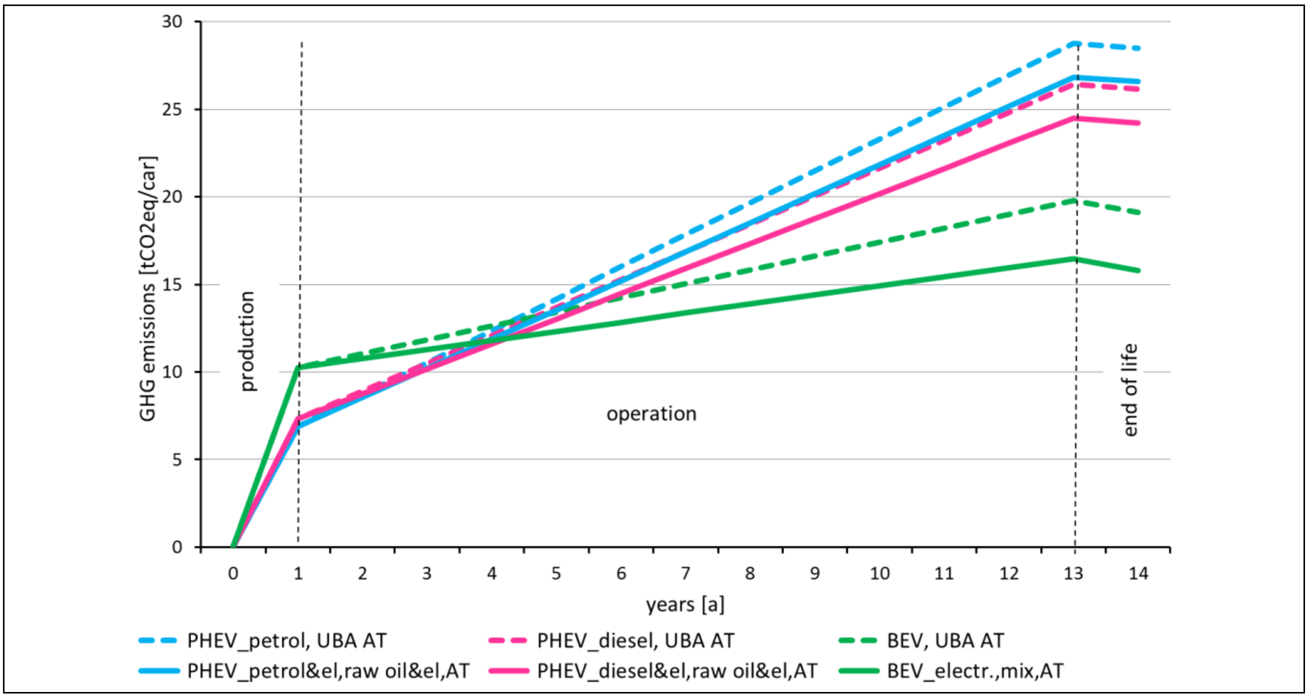

Figure 77: Comparison of the cumulated GHG emissions using the AT mix of UBA and the LCA tool

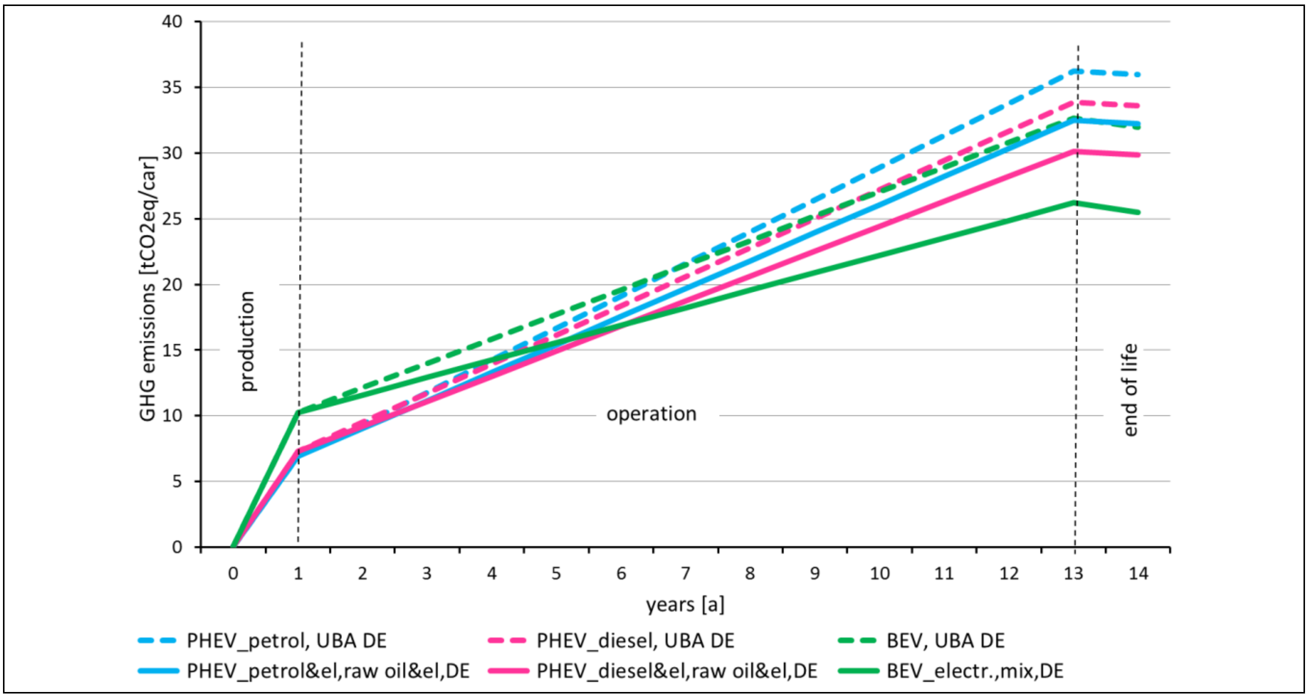

Figure 78: Comparison of the cumulated GHG emissions using the DE mix of UBA and the LCA tool

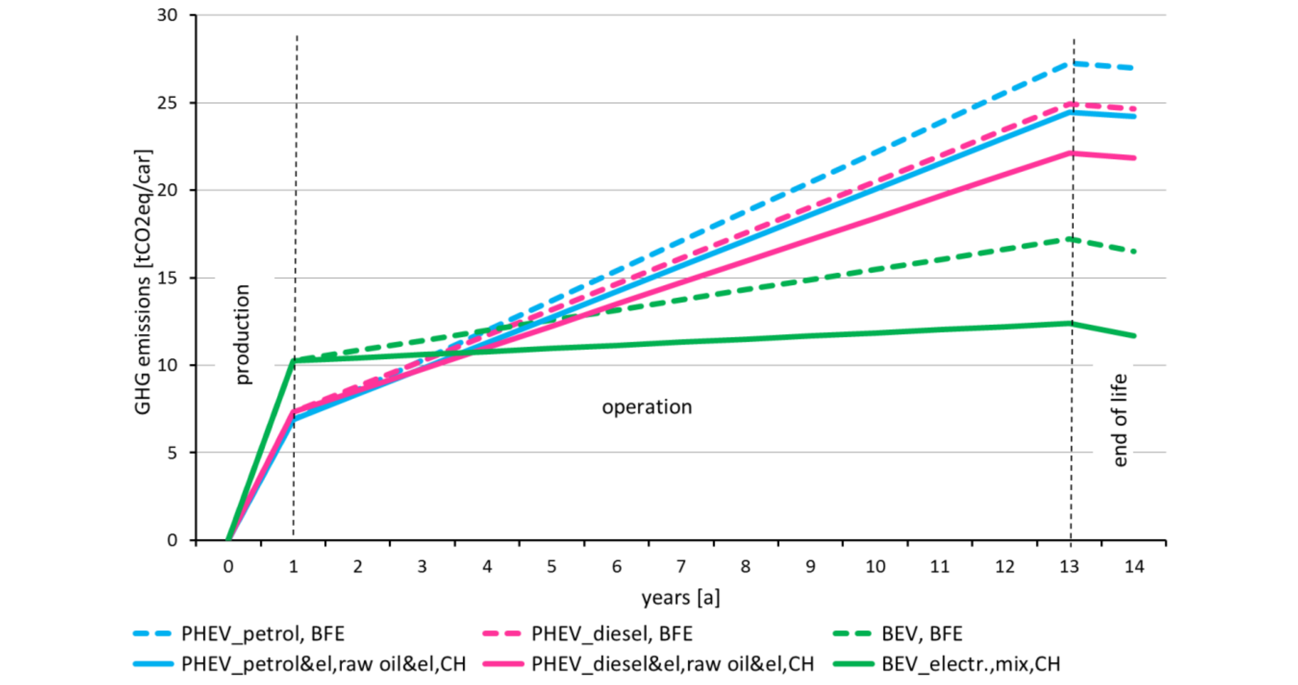

Figure 79: Comparison of the cumulated GHG emissions using the CH mix of BFE and the LCA tool

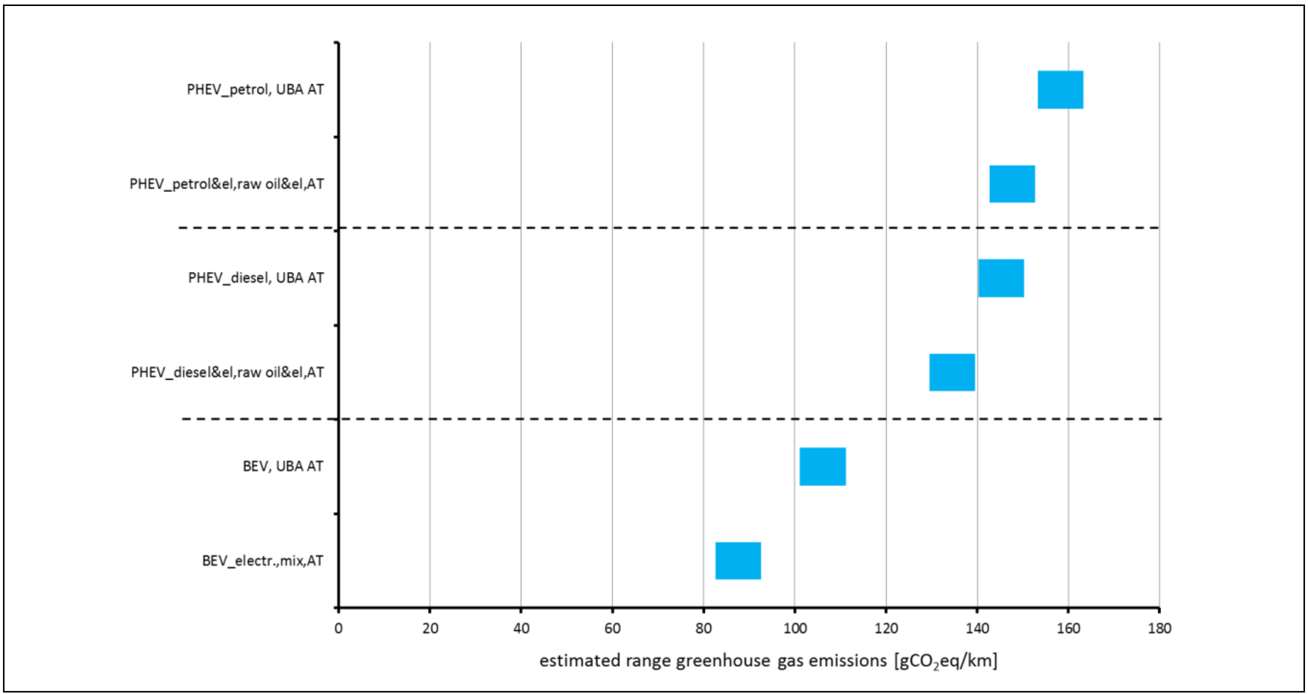

Figure 80: Comparison of the estimated GHG emissions per kilometre using the different electricity mixes in AT

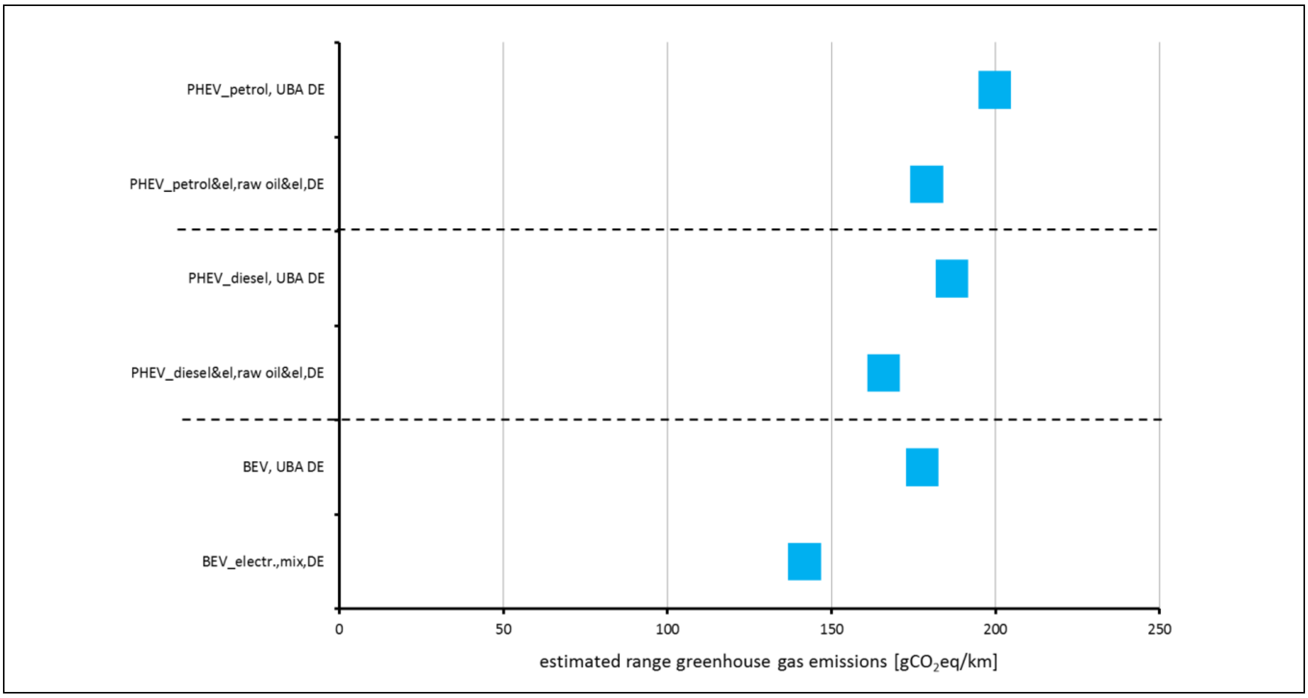

Figure 81: Comparison of the estimated GHG emissions per kilometre using the different electricity mixes in DE

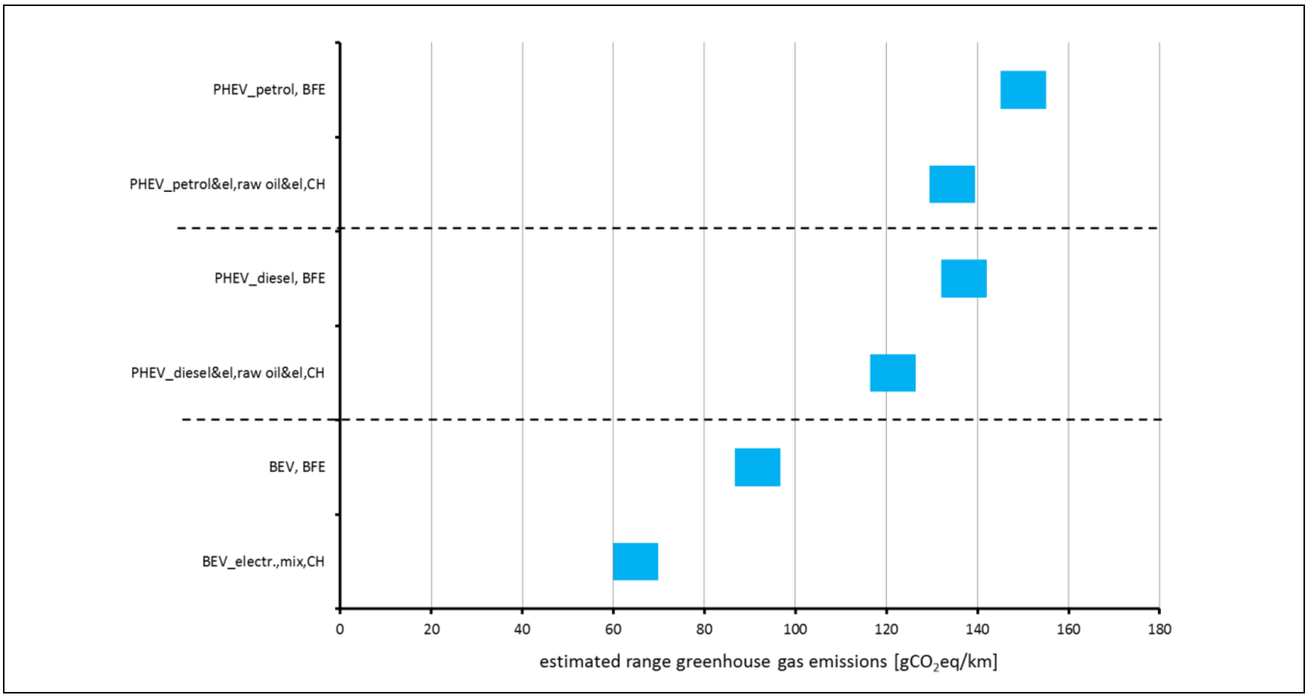

Figure 82: Comparison of the estimated GHG emissions per kilometre using the different electricity mixes in CH

10.2.5 References

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